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Contents

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PLANFORM CHANGES OF A BRAIDED RIVER WITH FINE SAND AS BED AND BANK MATERIAL

by

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ABSTRACT: As a first step towards the development of a predictive model for channel changes and related bank erosion, morphological processes were studied in a braided river with fine sand as bank and bed material. This was done using mainly (geometrically corrected) satellite images, the use of which was justified because of the large scale of the river studied: the Jamuna River in Bangladesh with a total width of up to 17 km. The study concentrated on bank erosion, channel shifts, and processes at bifurcations and confluences. It was found that the bank erosion depends on the relative curvature of the curved channels, and that the rate is an order of magnitude larger than predicted by Hickin & Nanson (1984). Several types of channel shifts were identified, and it was observed that cutoffs occur already at very low cutoff ratio's. The main conclusions from the study are that on the one hand much more studies are needed to improve the understanding of these different processes, and on the other hand that there is a clear limit to the period over which predictions can be made due to the observed chaotic behaviour of the channel changes.

1 INTRODUCTION

Understanding of future planform changes of rivers is essential for the siting of infrastructure (like embankments, supply canals, roads, etc.) and of towns and villages along rivers. Nowadays the understanding of planform changes of **meandering rivers** is fair: meandering via bank erosion can be predicted to some extent (Hickin & Nanson, 1984), including the occurrence of cutoffs (Klaassen & van Zanten, 1989), and predictive models for the development of meanders (Parker & Andrews, 1981; Crosato, 1990). No predictive models are available for **braided river systems**, although the need for predictions of future behaviour is even more accute, because of the apparently erratic behaviour of such river systems (Burger et al, 1988).

This paper reports on a study that was carried out to improve the understanding of the processes in braided river systems, with the ultimate aim to develop a deterministic method for predicting the future changes in channel planform and the corresponding bank erosion. Connected to this is the question whether there is a limitation as to the period over which bank erosion along a braided river can be predicted in advance. The present study was initiated in relation to the design of a bridge across the braided Jamuna River in Bangladesh. The Jamuna River is the lowest reach of the Brahmaputra River in Bangladesh (see Fig.1). Its main characteristics are a water level slope that gradually decreases form 0.10 to 0.06 m/km, the bed material is quite uniform and D_{50} varies from 0.25 mm near the Indian border to 0.16 mm at the confluence with the Ganges River, the average annual flood is about 60,000 m3/s, and during low flow between 4.000 and 12.000 m^3/s. The Jamuna River is a large braided sand bed river, the number of braids (during low flows) varies between 2 to 3, and the total width of the braided channel pattern varies between 5 and 17 km. Flood conditions usually prevail from May through October (see e.g. Coleman (1969)) while the low flow season lasts from December through March. For more details on the Jamuna River reference is made to Coleman (1969), Bristow (1985), Klaassen & Vermeer (1988a and 1988b) and RPT et al (1987, 1990a and 1990b).

Within the Jamuna Bridge Appraisal Study, an extensive analysis was made of rates of bank erosion along and channel processes in the Jamuna River in Bangladesh, using satellite images and cross-sections.

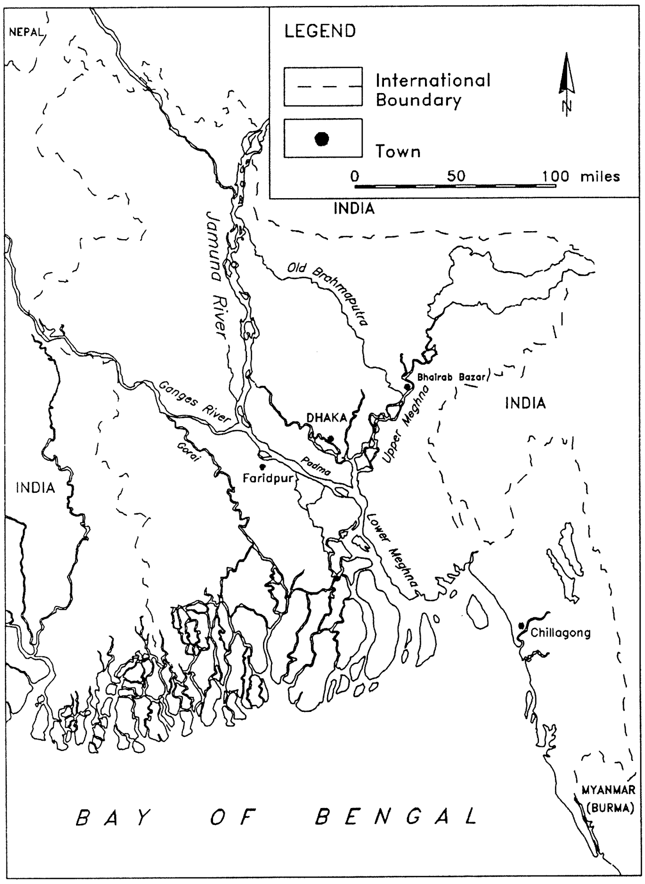

Fig. 1 Map of Bangladesh with Jamuna River

This paper summarizes the results of this study. For more details reference is made to Masselink (1989).

Several studies on the Jamuna River have already been carried out, leading to an increased understanding of the processes that take place in such large, braided sand-bed rivers (Coleman (1969), Bristow (1985), Klaassen & Vermeer (1988a,b), Klaassen et al (1988)). These studies have revealed processes that take place on a scale which can not be compared to the results of studies on "normal" braided rivers (see e.g. Rust, 1972). In particular the use of satellite images in the present study does enhance the understanding of the processes in the Jamuna River substantially. Because of the large scale of the river involved the accuracy of the LANDSAT MSS images, in combination with the rapid and substantial changes, makes the use of the satellite images very fruitfull. For the time being, SPOT images are not a real alternative as (i) they cover a much shorter period and (ii) the detailed insight they provide, is not really needed in this stage.

2 APPROACH

2.1 Data used

Yearly bank erosion rates were studied on the basis of comparisons of geometrically and otherwise corrected satellite images. Here LANDSAT MSS images of in total 6 years were used, with time intervals of 1, 2 and 6 years. The data that were used in this study comprised cross-sectional data and planform data derived from LANDSAT images.

2.2 Cross-sectional data

The cross-sectional characteristics of the Jamuna River were studied on the basis of soundings made by the Bangladesh Water Development Board (BWDB) since 1966. The locations of the studied cross-sections are indicated in Fig. 2.

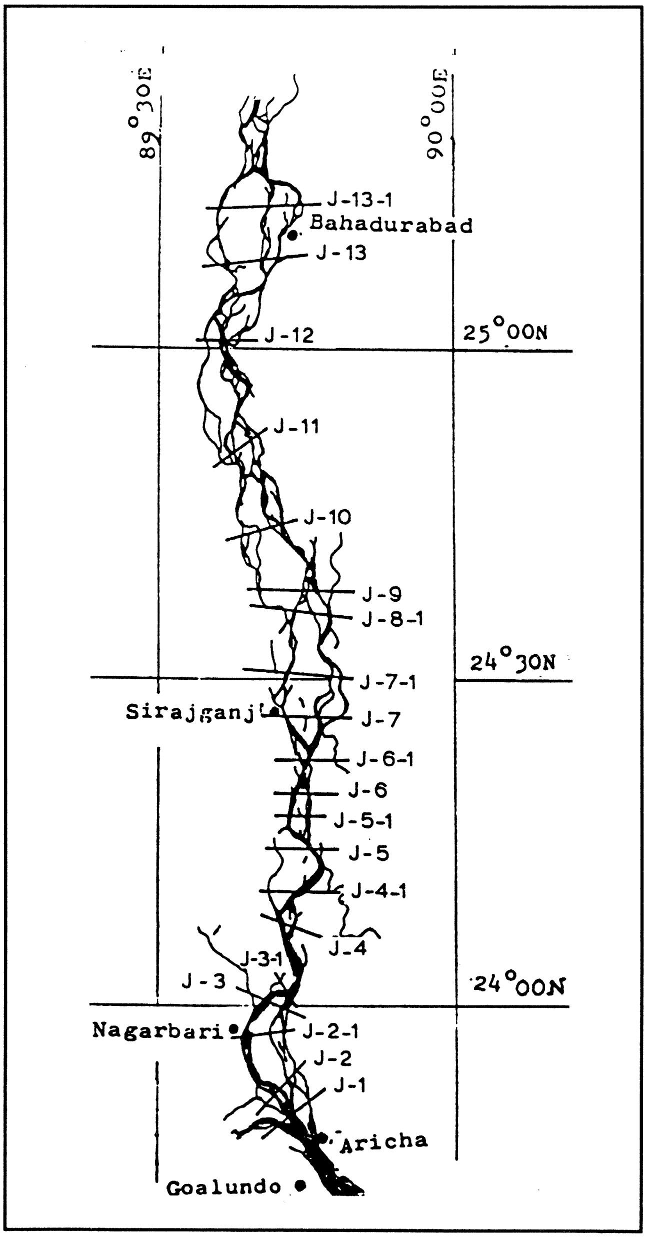

Fig. 2 Location of BWDB cross-sections

An extensive analysis of all cross-sections has been carried by Klaassen & Vermeer (1988a). They concluded that over the last decades the Jamuna channel bed was stable both laterally and vertically. Hence, the Jamuna River is on the average not aggrading, and can be supposed to be in equilibrium.

2.3 Selected satellite images

For the LANDSAT MSS images selected see Table 1.

Image Scene number[1])	South 138-43	North 138-42
Year	Date	Date
1976	4 Mar	-
1977	9 Feb	9 Feb
1978	22 Feb	-
1984	23 Feb	23 Feb
1986	20 Feb	20 Feb
1987	7 Feb	7 Feb

[1]) LANDSAT 4/5 numbering

Table 1 LANDSAT images used for the present study

The research was primarily based on the images of the Southern part of the Jamuna, because these images form a more or less continuous series, whereas the Northern images did not. Only images were selected for dates for which the stage at Sirajganj (see Fig.2) was between 6.00 and 7.00 m+PWD (PWD refers to the agreed reference level in Bangladesh). Hence, all images show the Jamuna River during low flow conditions. The images were geometrically corrected (de Jong, 1988), hence mutual comparisons between different years could be made.

2.4 Classification

In a next step the images were classified according to the type of soil and the vegetation cover. For this an algorithm was applied, using two spectral bands. For the procedure applied see Klaassen et al (1988) and de Jong (1988). The following classification and corresponding colour coding was adopted:
- water : blue;
- bare land : grey ;
- sand : orange;
- vegetation : green.

The classified images are called statical composites. An example of a series of these statical composites is given in Fig. 3. Because it concerns a black and white copy, here the water corresponds to the darkest colour. Changes over the years in water and sand distributions are obtained by comparing statical composites. An "overlay" (of the digital data) of two statical composites is made, and based on the four identified classes, there are 16 possible combinations, yielding 16 new classes. These can subsequently be interpreted and analyzed. The new picture obtained (being the comparison of two succesive years) is called a dynamical composite.

2.5 Processing, analysis and interpretation

The statical and the dynamical composites were used, together with the BWDB cross-sections, for the study of processes active in this braided river system. The following topics were investigated:
(1) bank erosion rates of curved channels,
(2) cutoffs,
(3) processes at bifurcations,
(4) processes at confluences.
The rationale for selecting these topics is that it is felt that these processes in combination are responsible for the changes in channel patterns. The results of the various analyses are presented in the subsequent Chapters 3 through 6.

The different processes were studied via measurements in the statical and dynamical composites. The accuracy of the LANDSAT-image after processing is approximately 200 meters at a significance level of 97%. De Jong (1988) presents a complete discussion on the selection, processing, classification and accuracy of the images.

3 BANK EROSION RATES

3.1 Bank erosion rates

Using the dynamical composites, the bank erosion rates along curved channels could be studied. Not all curved channels were included in the analysis: channels that had significantly narrowed or widened in one or two years were excluded, as for these cases it was difficult to distinguish between bank line changes due to an increase or decrease of discharge and 'true' bank erosion. The bank erosion does obviously vary along the bend: here only the maximum bank erosion rates were studied.

Fig. 4 provides a summary of the observations for the four dynamical composites of the south image, via a plot of the observed erosion rates (divided in classes) versus the number of observations in each class. Yearly erosion rates E apparently vary between 0 and 1,000 m. Fig. 5 provides the same information, but here the average number of occurrences for the four different periods is presented. It appears that the bank erosion rate along the curved channels of the Jamuna River in most of the cases is between 0 and 500 m/year with larger values up to 1,000 m/year under exceptional conditions. This is conform the findings of Coleman (1969).

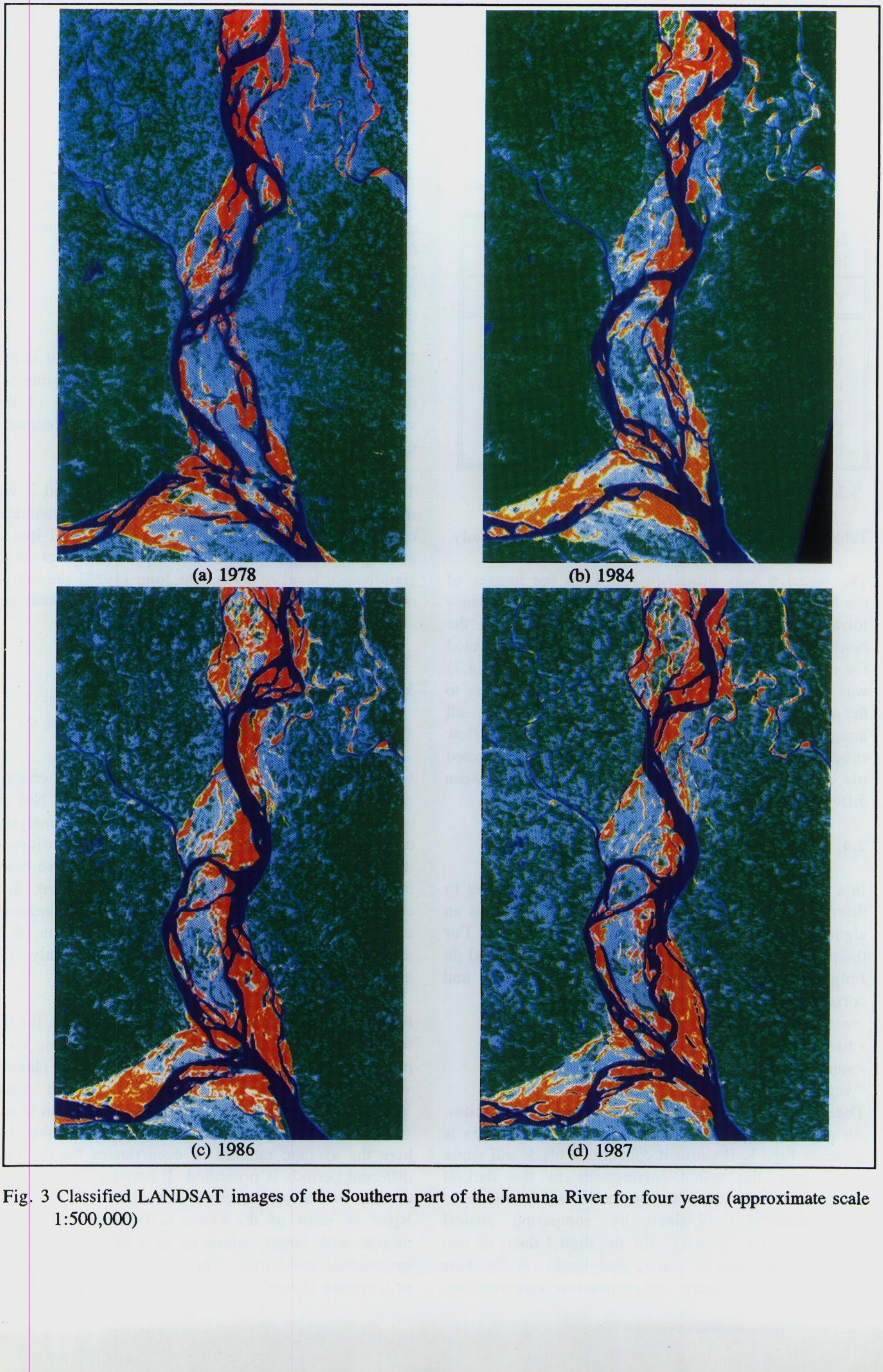

Fig. 3 Classified LANDSAT images of the Southern part of the Jamuna River for four years (approximate scale 1:500,000)

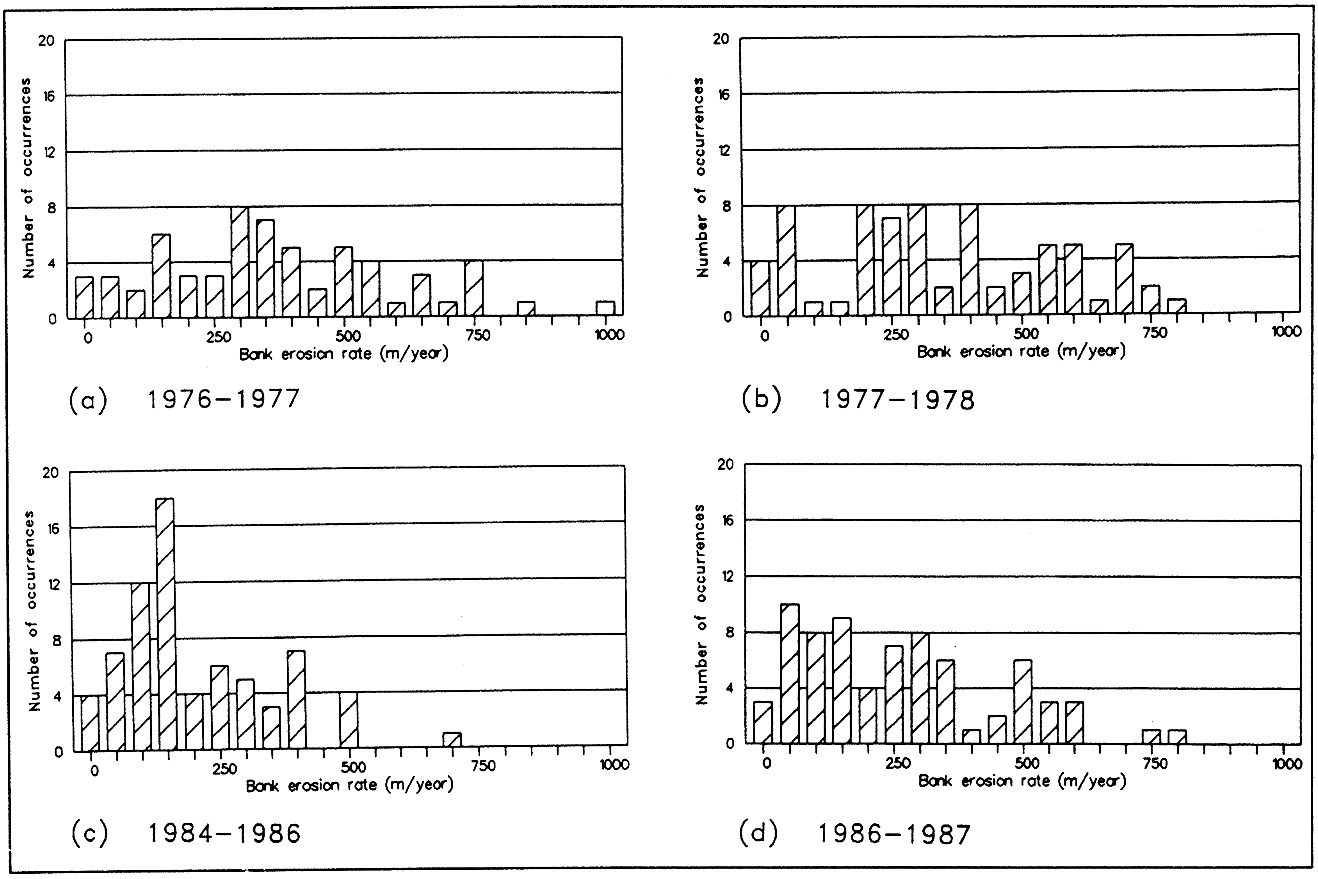

Fig. 4 Observed bank erosion rates along curved channels of the Jamuna River

Also some other aspects of the bank erosion were studied using the satellite images. The direction of the bank erosion was studied by plotting in Fig.6 the direction of the maximum erosion relative to the valley slope. The direction of the largest erosion is on the average approximately perpendicular to the valley slope, while for smaller erosion rates it frequently deviates substantiaaly from the valley slope.

Also the influence of vegetation was studied. It was found that chars with minor or absent vegetation do not erode faster than vegetated floodplains along the

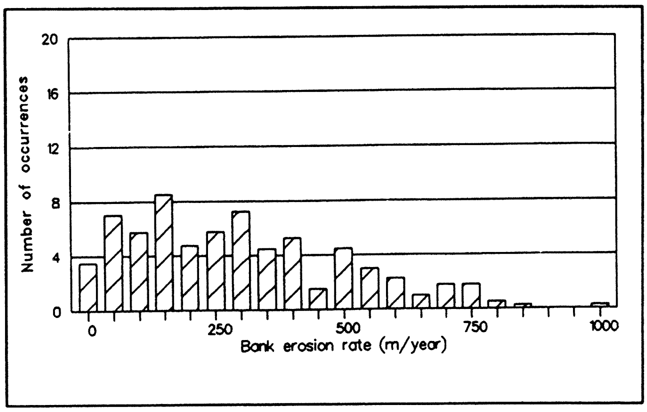

Fig.5 Average bank erosion rates along curved channels of the Jamuna River for the four periods considered in Fig. 4

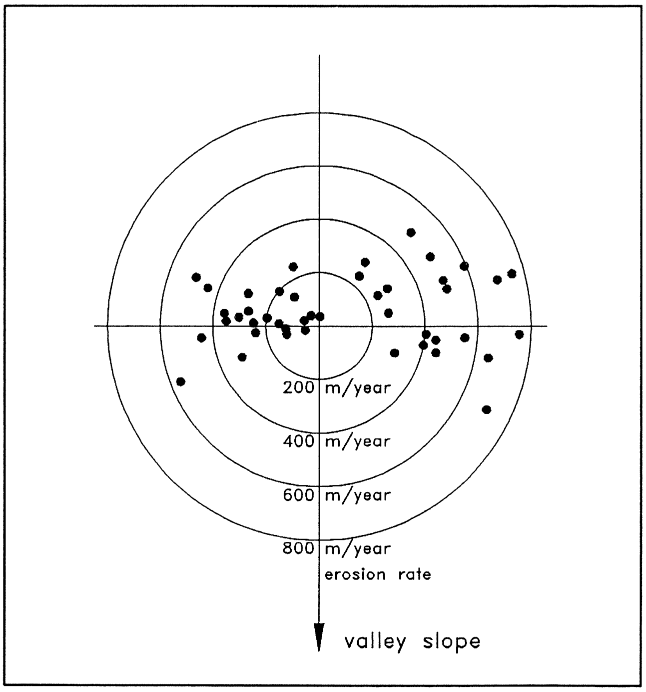

Fig. 6 Direction of bank erosion along curved channels of the Jamuna River

edge of the channel pattern. Hence it can be concluded that for the deep channels of the Jamuna River (see Klaassen & Vermeer, 1988b) the influence of vegetation only effective in the upper layers is negligible.

Furthermore a distiction was made between the following bank erosion mechanisms (see the below Fig. 7): rotation (A), extension (B) and translation (C).

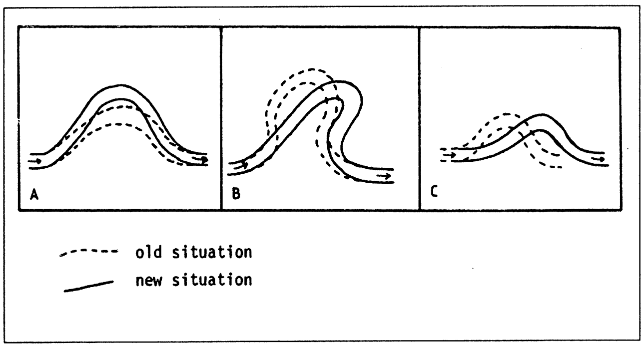

Fig. 7 Possible bank erosion mechanisms studied here

It was found that both rotation and extension do occur; translation is absent along the Jamuna braids. Translation does usually occur for cohesive banks. The chars and flood plain deposits of the Jamuna River exhibit hardly any cohesion, so this may be an explanation.

Finally it is remarked that apparently the yearly flood hydrograph may play a role in the magnitude of the yearly erosion rate (see the difference between e.g. 1976-1977 and 1984-1986). This has not been explored in more detail yet.

3.2 Analysis

The observed bank erosion rates were analysed within a frame-work similar to previous work by Nanson & Hickin (1985) for meandering rivers, by establishing the relation between the bank erosion rates and the relative curvature of the channels. Here a complicating factor is the fact that not one channel is considered, but that several parallel braids are present. In a meandering river the bankfull width is fairly constant (and fairly good related to the 'dominant' discharge). In the present case the width of a channel will differ depending on whether the channel is in regime, scouring or vanishing. This makes scaling with the width W as parameter (as done by Nanson & Hickin) more risky. Nevertheless this has been attempted hereafter.

According to Nanson & Hickin the yearly bank erosion E (in m) can be expressed as:

$$E = f(W, R/W, C, B) \qquad (1)$$

where E = yearly bank erosion (m), W = channel width (m), R = radius of curvature of the curved channel (m), C = Chezy coefficient ($m^{1/2}/s$), that represent the channel roughness, and B = overall bank resistance coefficient. For the time being it was assumed that the parameters C and B do not vary along the Jamuna River, hence for this river the equation would reduce to :

$$E = f(W, R/W) \qquad (2)$$

This expression was tested for the Jamuna bank erosion data. The determination of the applied radius of curvature was done in the following way. Usually the values of relative curvatures (R/W) for the two years were averaged. If, however, one of the values for R/W was smaller than 5.0, and the other was greater than 5.0, then the value of the bend with the smallest relative curvature was used. The reasoning behind this choice is that it was considered that this bend was most active in the eroding process.

Initially a distiction was made as to the channel width: four classes were identified (see Fig. 8). The results, related to bends selected according to the criteria given in Section 3.1, are presented in Fig. 8. It can be observed that the largest channels tend to correspond to the largest erosion rates. Hence a similarity collapse was attempted, by plotting E/W versus R/W. The result is given in Fig. 9.

Upon inspection of Fig. 8 and Fig. 9 the following observations can be made:

(1) There is definitely a negative correlation between the relative bend curvature (R/W) and the erosion rate (E/W). Low relative curvatures lead to relatively fast erosion rates, and vice versa. There is no tendency for very sharp bends (R/W < 2.5) to have smaller erosion rates, as was observed for meandering channels by Nanson & Hickin (1984). The value of W used here corresponds to the low flow width. As on the average the bankfull width is about 3 times larger (Klaassen & Vermeer, 1988a), a possible peak would have occurred here for the low flow data for R/W-values of approximately 7.5.
(2) The largest bends (W > 1000 m) plot low in Fig. 9, indicating that relative erosion rates by large channels is relatively small. However, only 7 large channel bends were studied. From Fig. 8 it appears that there is no significant difference in relative erosion rate between the smallest (W < 500 m) and the intermediate (500 < W < 1000 m) channels.
(3) Both Fig. 8 and Fig. 9 show a substantial scatter. Apart form the assumptions made during the

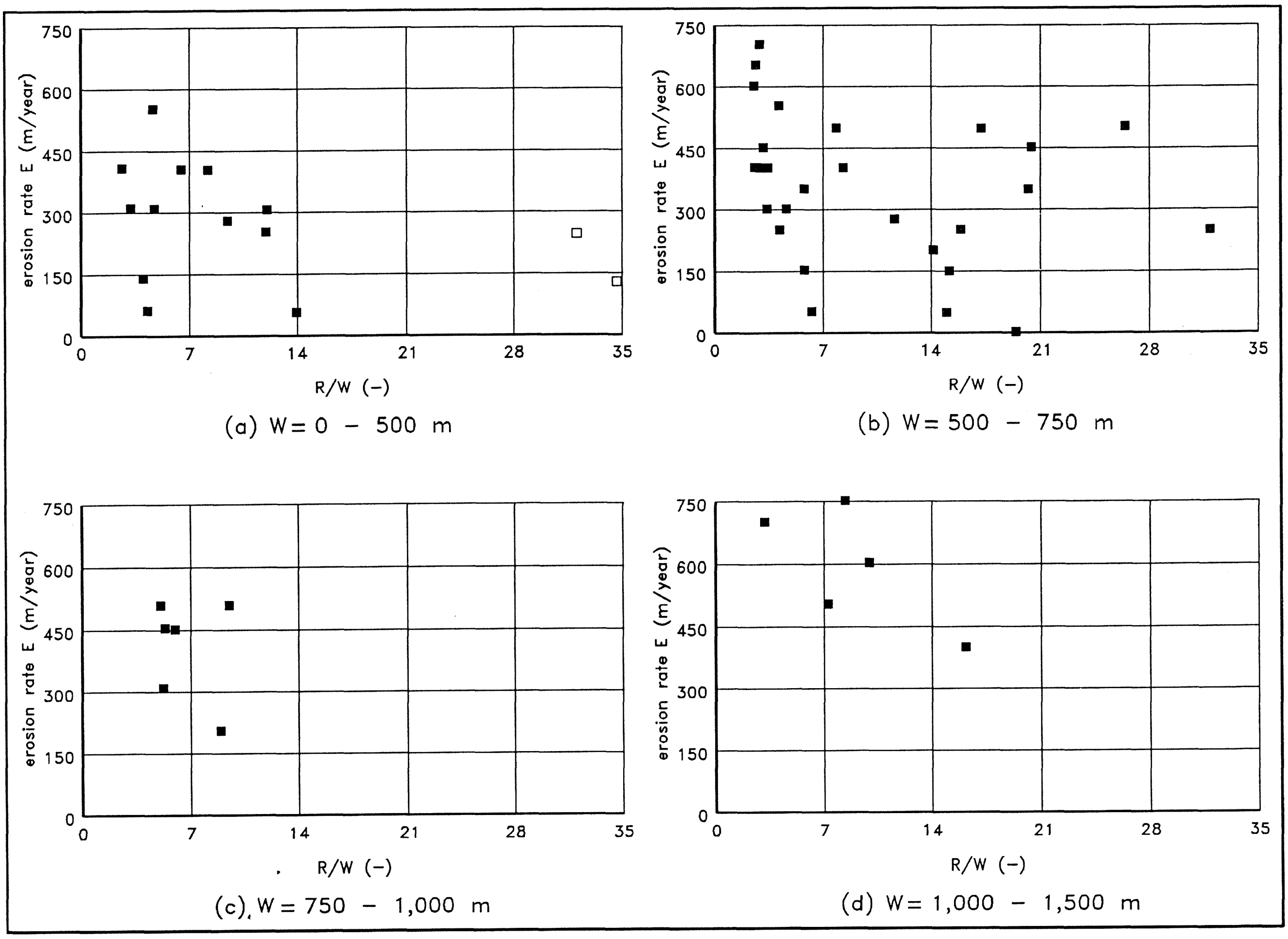

Fig. 8 Dimensionless erosion rate E/W versus R/W for the channels classified according to width

derivation of Eq. (2), possible explanations for this scatter may be:

- measuring accuracy (see before);
- use of low flow widths;
- use of one value of the radius of curvature, where in reality R may vary considerable along the bend;
- the inclusion of less active bends possibly being rather shallow.

A comparison was made between the presently observed erosion rates and the rates predicted byHickin & Nanson (1984). Assuming a bankfull discharge of a channel of 20,000 m^3/s and using the other river characteristics described in Chapter 1, the estimate of several tens of meter of erosion a year. It is clear that this estimate is an order of magnitude smaller than what was actually observed. A possible

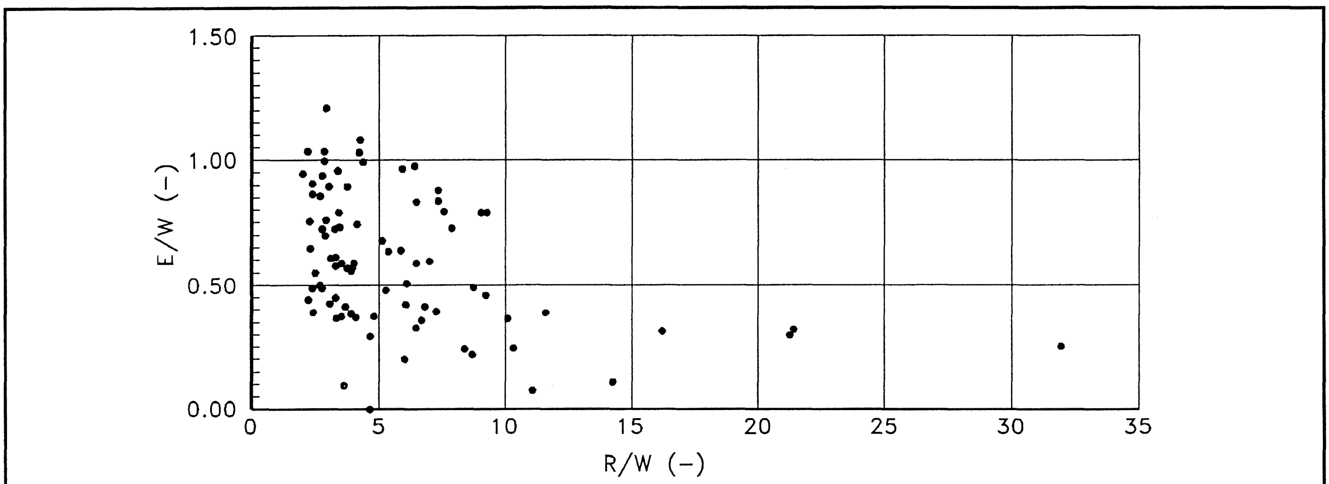

Fig. 9 Dimensionless erosion rate E/W versus R/W for all curved channels along the Jamuna River

explanation could be that in the case of the Jamuna River, the floods extend over a period of some three months. It may be appropriate to include in any prediction method also the duration (and magnitude?) of the floods.

4 CHANNEL SHIFTS

Using the dynamical composites, also channel shifts were studied. The channel pattern of the Jamuna River changes continuously: large channels being abandonned, and new channels developing in a few years only, are common features. Coleman (1969) refers to this process as to 'sudden shifts'. A channel shift is accomplished by the development of a completely new channel, or, more common, a pre-existing channel takes over the conveyance function of another channel. The new channel may flow through the original channel deposits or through the floodplain. Three types of channel shifts were identified and these are discussed hereafter:

(1) Bar induced shifting

Sand bar induced channel shifting is not often identified in the literature, but is a rather important process in the Jamuna River. Large sand bars migrating in a channel or developing in specific channel reaches block the entrance of small channels. Consequently these channels will receive less discharge and are "abandonned" subsequently. Sand bars can also redistribute the flow so that one channel receives more discharge than another. A complete channel shift can be the result (see Fig. 10).

(2) Development of a cutoff

The development of a cutoff occurs frequently. Of the 23 cases of channel shifts studied, 11 relate to cutoffs. To get some insight into this phenomena, it was approached in two ways, notably (i) considering the relative curvature R/W, and (ii) considering the cutoff ratio (Klaassen & van Zanten, 1989).

Re (i) Relative curvature

The relative curvature of a bend is assumed to be a primary control on the processes which determine channel shifts of this type. From a study of channel shifts, it appeared that the average relative curvature (R/W) of the pre-shift bends was 3.6 (standard deviation 1.8). Bends with R/W-values < 3.6 are apperently 'unstable' and result in a channel shift within a period of two years. This may be explained by the shear stress distribution in the bend.

Re (ii) Cutoff ratio

Klaassen & van Zanten (1989) have shown the importance of the cutoff ratio λ, being the ratio between the length of the channel along the curved reach and the direct line, along which the cutoff channel is developing. For a number of cutoffs in the Jamuna River the value of λ was determined and a cumulative frequency distribution was prepared. The

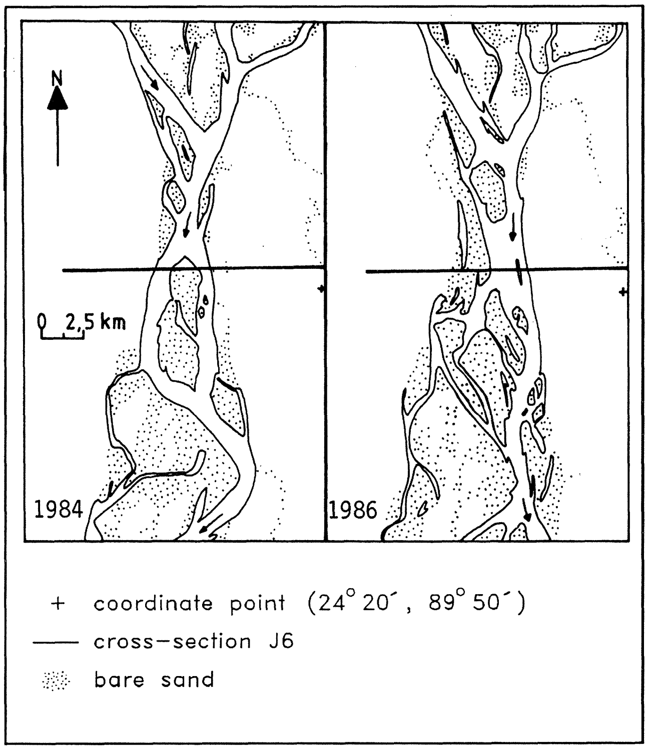

Fig. 10 Bar-induced channel shift

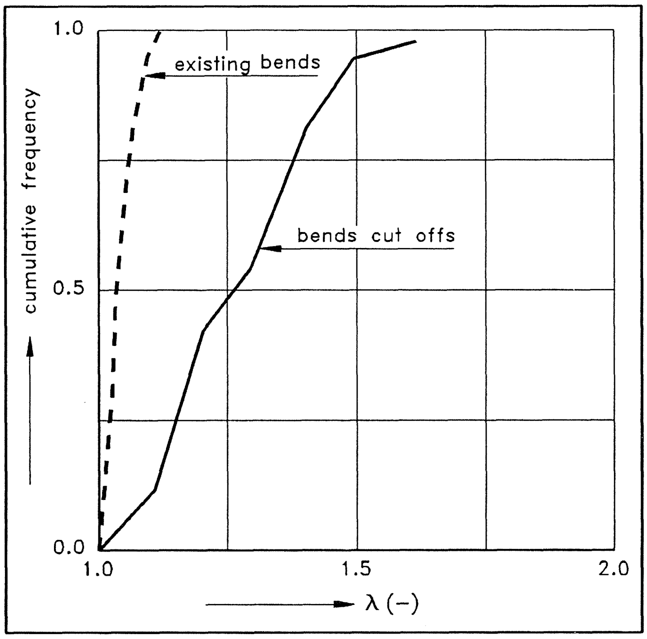

Fig. 11 Cumulative frequency distribution of cutoffs compared with existing bends

results are presented in Fig. 11. It appears that the values of λ vary between 1.0 and 1.7. These are very low values for the cutoff ratio, demonstrating that in this type of braided river with fine bed material channel shifting via cutoffs occurs relatively quickly. For comparison: in meandering rivers values of λ in the range of 5 to 30 have been observed (Joglekar, 1970; Klaassen & van Zanten, 1989). Furthermore it is observed that the 'critical' value of λ varies between a wide range, hence the usefullness of Figure 11 for predictive purposes is very limited. For the time being a 50% value of 1.25 can be used.

In Fig. 11 also the frequency distribution of potential cutoff ratio's of existing bends is added, and it is observed that larger (potential) values of λ apparently result almost immediately into a cutoff.

(3) Outerbend channels in bends

Also the formation of what is called here an outer bend overflow channel occurs frequenly (9 times out of the 23 cases studied). Also this may be related to the shear stress distribution in the bend (Masselink, 1989). Often such an outer bend overflow channel developes where previously an old channel has been present. See Fig. 12 for an example of the development of an outer bend channel, where a fairly rapid shift took place. The new channel started as an outerbend overflow channel and was located in the floodplain. Within two years (1979-1981) the overflow channel deepened from 7 to 17 metres, and the original channel had been filled in completely. The original channel is not always filled in completely, but may still convey a certain amount of discharge.

The previously discussed types of channel shifts were rather simple in that a clear cause and effect relationship could be determined: e.g. a sand bar blocks a channel, and consequently the channel is abandonned. Many channel shifts occur without such an obvious reason. Usually sand bar formation enhances a channel shift, but it is not the direct cause. It is proposed that changes in flow and sediment distribution cause local bed aggradation in one channel. Consequently the flow efficiency of this channel is reduced through a decrease in channel slope. Sand bar formation may occur. Another channel may take over the function of the aggrading channel because of its higher efficiency. All depends on the complex interaction between channel morphologhy, discharge and sediment load. This relationship is too complex to be studied on the basis of LANDSAT images alone. Complex channel shifts are a fairly important process in the Jamuna River, the reasons why such shifts take place however, are not fully understood.

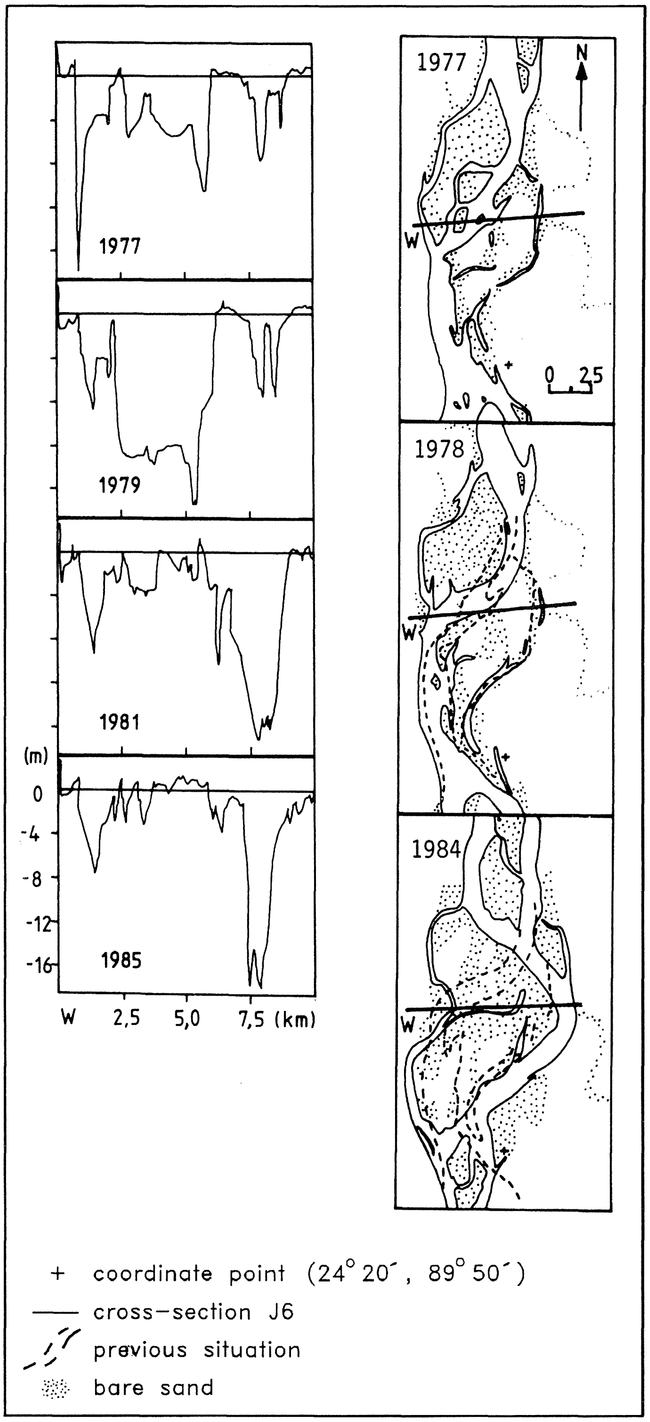

Fig.12 Development of an outer bend channel into an already existing old channel

5 PROCESSES AT BIFURCATIONS

When a major channel continues in two smaller channels, a bifurcation is present. A bifurcation is a very important feature in a braided river system, as the development in time of the two bifurcating channels is determined by the flow and sediment distribution at the bifurcation. Here a description is given of the processes that are active at a bifurcation. The two channels arising from the bifurcation are separated from each other by a char; the surface of this char is above bankful discharge level.

The development of the bifurcation depends on the character of the planform; it may be a symmetric or an a-symmetric one. A symmetric bifurcation is characterized by the flow direction of the upstream channel being different from the two downstream channels. A symmetric bifurcation is characterized by upstream accretion. An analysis of several large bifurcations revealed an average propragation speed (in upstream direction) of approximately 900 m/year.

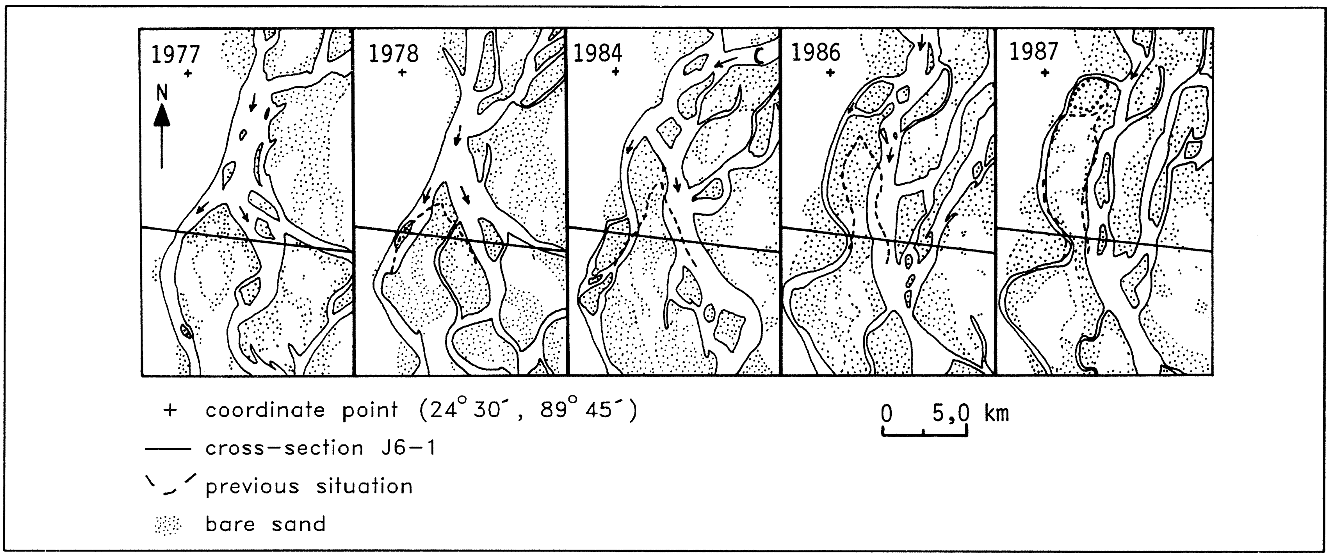

Fig. 13 Development of a bifurcation during the period 1977-1987

(in upstream direction) of approximately 900 m/year. It appears that the propagation rate scales with the size of the channels.

An a-symmetric bifurcation is characterized by one of the downstream channels having approximately thesame direction as the upstream channel. The other downstream channel is usually much smaller in size,and because of blocking of this smaller channel by chars, it usually disappears in one or two years.

Fig. 13 outlines the development of a bifurcation in the period 1977-1987. The behaviour is characterized by a symmetric and an a-symmetric phase. In the period 1977-1984 a symmetric bifurcation is observed which progrades in an upstream direction at a rate of about 625 m/year. Between 1984 and 1986 a major channel upstream of the bifurcation (marked with a c on the drawing for 1984) is abandoned. The result is an asymmetric bifurcation where the eastern bifurcation channel is transporting most of the discharge. A small char is formed, blocking the entrance of the western channel. In 1987 the small char is attached to the major char and the bifurcation point has disappeared.

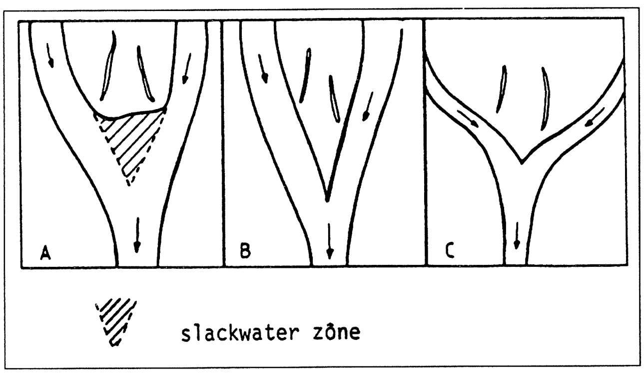

Fig. 14 Different types of confluences

6 PROCESSES AT CONFLUENCES

The development of a confluence appears to depend on its shape. Different shapes of confluences are schematically drawn in Figure 14. They are different in the presence of a slackwater zone (A versus B and C) and in the angle between the two confluencing channels (B versus C). A slackwater zone is prone to quick deposition and usually vanishes in one year. The channels that drain the char surface have an important role. The char surface slopes in downstream direction so most of these channels discharge near the confluence. If they discharge in the slackwater region all the sediment load is depositing there, giving a significant contribution to the downstream accretion. If the confluence is a smooth one, all the sediment will be discharged in the main channel and be transported downstream. In this case these channels may even lead to erosion of the confluence as most of their sediment load is extracted from the downstream part of the bar.

Bristow (1985) mentions downstream accretion is an important mechanism for the growth of medial chars (major bars in main channels). In the present study this was not confirmed for the major confluences studied here. In general if the confluence margin is smooth, and the two confluencing channels do not change significantly, confluences are relatively stable river sections. This corresponds to the conditions in the Yellow River, where some of the nodal points are formed by channel confluences (Chien, 1961). If on the other hand one of the channels becomes dominant, the confluence moves in the direction of the minor channel by means of erosion at the major channel side of the confluence, and sedimentation at the minor channel side. On the average, confluence points do not move significantly upstream or downstream.

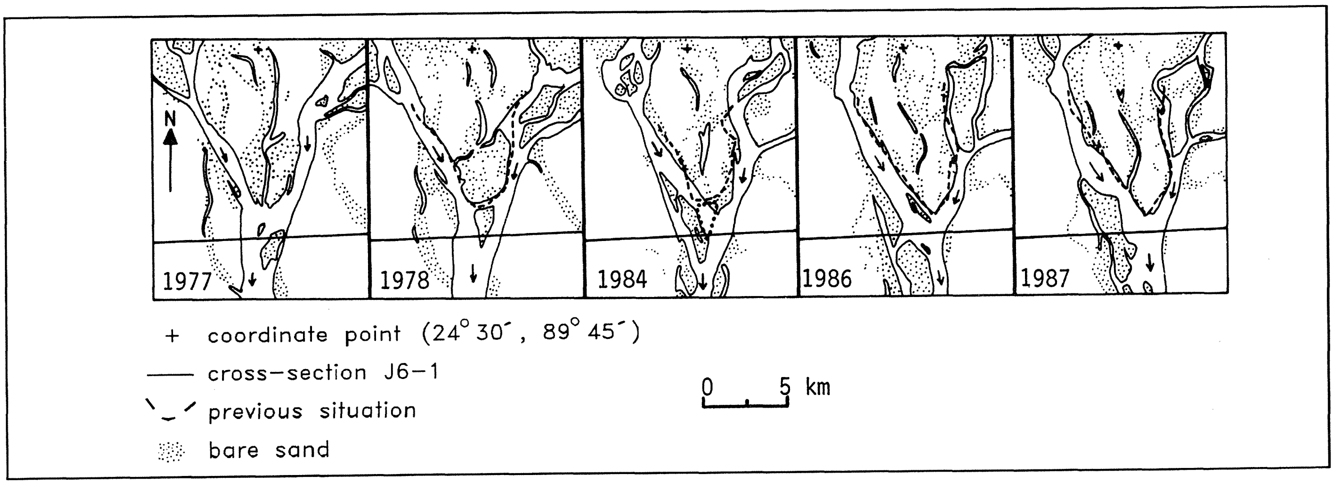

Fig. 15 Development of a confluence in the period 1977-1987

As an example here the historical development of a confluence near Sirajganj over the period 1977 -1987 is shown Fig. 15. This confluence had a fairly blunt shape in 1977. In 1978 a bar had been formed by sedimentation in the slackwater region, smoothing the confluence. Over the period 1978-1984 the western channel became more important, and the conflunce migrated to the east. In the period 1984-1987 the situation did not change significantly, and over the whole period the position of the confluence is remarkable stable. Old maps, however, show that the conflunce was not present at this particular location in the 19th century. Hence, this so-called nodal point (Coleman, 1969) is probably more determined by the presence of a confluence in the last decades than by other possible causes, like larger resistance to erosion due to deposits of a former river (Coleman, 1969).

7 TOWARDS A PREDICTIVE MODEL?

The ultimate objective of this study was to investigate whether the development of a predictive model for braided rivers with fine bed and bank material is feasible. With such a deterministic model one should be able to predict future channel development and related bank erosion with reasonable accuracy and preferably on a time scale of at least several years.

From the results of the study reported here it can be concluded that presently it is not possible to develop such a deterministic model, for at least two reasons:

(1) the limited understanding of the prevailing processes, and
(2) the observed chaotic behaviour of the system.

These two reasons are discussed hereafter.

Re (1) Limited understanding

Even for the limiting assumptions made here (e.g. in the analysis of the bank erosion rates that the channel should not 'deteriorate' too much over the period of comparison), the resulting relationships exhibit a large scatter. This is a.o. caused by not including all relevant features in the analysis. Some examples of this are:

(1) The analysis was generally based on the LANDSAT images from which only two-dimensional features can be studied. The BWDB cross-sections (taken only every 4 km) were only of limited help. Especially channel shifts are strongly influenced by the surface morphology. Relatively low parts of the floodplain are prefered locations for new channels, and generaly such locations cannot be determined from LANDSAT images.
(2) The studied images form a discontinuous series (1976 (only partly usable, because of cloud cover), 1977, 1978, 1984, 1986, 1987). Consequently the development of a bend or a secondary channel could only be "followed" for two succesive years. After the 'gap' that then followed, usually the bend or secondary channel did not exist anymore.
(3) The shape of the discharge hydrograph was not yet taken into account in the analysis of e.g the bank erosion rates. The same holds for channel shifts: Klaassen & van Zanten (1989) have shown theoretically that the magnitude of the flood and its duration) are important parameters in the actual occurence of a cutoff.

Re (2) Chaotic behaviour

Morphological processes in braided rivers like the Jamuna River ('choked with sediment', because of the fineness of the bed material and the large sediment loads during floods), appear to be characterized by chaotic behaviour, and this makes it difficult if not impossible to model the morphological processes in a deterministic way. A.o. sand bar induced channel shifting is producing this chaotic behaviour, but also the discharge hydrograph being different for different years adds to the chaotic behaviour.

The results of the present study imply that for the time being predictions can be made, but only for the conditions one or two years ahead. The only locations for which predictions can be made for a longer period ahead are the nodal points (major confluences), which appeared to be quite stable over decades.

8 CONCLUSIONS AND RECOMMENDATIONS

Based on the study reported here, the following conclusions can be drawn:

(1) The study of the satellite images, in combination with cross-sections has provided an improved understanding of changes in channel pattern of and the related bank erosion along large braided rivers with fine sand as bank and bed material.

(2) This improved understanding relates especially to the relation between the erosion and the relative curvature (R/W), the negligible importance of vegetation on bank stability, the occurrence of channel shifts and the importance of sand bars, the propagation in upstream direction of bifurcation when the two channels are of almost equal importance, and the stability of major confluences.

(3) Nevertheless, the understanding of these processes is still very limited, and does not allow for the development of a deterministic model for the development of the channel pattern and the prediction of where bank erosion will take place and how large the bank erosion will. Only near confluences prediction over some years may be possible, because usually these reaches are fairly stable.

(4) The fact that a deterministic model cannot be developed, is not only due to the as yet too limited insight in the processes in these rivers, but probably also to chaotic behaviour.

Based on these conclusions, the following recommendations are made:

(1) to study the morphological processes in more detail by:
- including also information over channel dimensions, in particular the relative importance of eroding channels,
- studying a more continuous series of satellite images,
- to include other aspects in the analysis like the duration of the yearly hydrograph;

(2) to carry out a special study into the possible chaotic behaviour of the river system, with the aim to identify this chaotic behaviour and to study its implications for the time span over which a reliable prediction of channel changes and bank erosion can be made.

9 ACKNOWLEDGEMENTS

The study discussed here is part of the Jamuna Bridge Appraisal Study Phase II, which is funded by UNDP, the World Bank being the executive agency. The study was carried out by the combination RPT (Rendel, Palmer and Tritton, U.K.)/ NEDECO (Netherlands Engineering Consultants)/BCL (Bangladesh Consultants Ltd.); the JMBA (Jamuna Multipurpose Bridge Authority, Bangladesh) is the client. DELFT HYDRAULICS is one of the partners of NEDECO for this study. The study was also partly funded by internal research funds of DELFT HYDRAULICS. The processing and classification of the LANDSAT image data was done by the National Aerospace Laboratory, The Netherlands. In particular the contribution of Messrs. H. Noorbergen and W. Verhoef is acknowledged in this respect. Mr. Z. de Jong took care of the geometrical correction and carried out a detailed study of the accuracy of the LANDSAT data.

LIST OF SYMBOLS

B = bank erosion coefficient
C = Chezy coefficient ($m^{1/2}/s$)
E = yearly erosion (m)
R = radius of curvature (m)
W = channel width (m)
λ = cutoff ratio (-)

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ON THE PREDICTION OF PLANFORM CHANGES IN BRAIDED SAND-BED RIVERS

Gerrit J. Klaassen[1], Erik Mosselman[2] and Hartmut Brühl[3]

ABSTRACT

Braided sand-bed rivers are characterized by rapid planform changes. The prediction of these changes requires a thorough insight into the morphological processes in this type of rivers. We report an ongoing study in which these morphological processes are studied on the basis of a series of satellite images covering almost all years in the period 1973-1992. The ultimate aim of this study is to develop a model for planform changes in braided sand-bed rivers. Possibilities and limitations of such an approach are discussed and the concept of the model is described and examplified with an application to a reach of the Jamuna (= Lower Brahmaputra) River. From analyses it has become clear that it is not possible to develop a fully deterministic model. Predictions of planform changes can only be done by including the probability of occurrence of the different potential developments. This is the more so because recent work suggests that some of the individual processes might exhibit chaotic behaviour. Hence, the model under development can be visualized as a gradual transition from a mainly deterministic model for the first year to a fully stochastic model for a more extended period.

INTRODUCTION

One of the projects of the Flood Action Plan (FAP) for Bangladesh is the Bank Protection and River Training Pilot Project (FAP 21/22). Within the framework of this project, which has a duration of 5 years, some test structures (groynes and revetments) have to be constructed along the braided Jamuna River (see Figure 1), and the performance of these structures has to be monitored. Lessons have to be learnt from the experiences obtained during the monitoring and maintenance, ultimately leading to guidelines for the design of bank protection structures along the Jamuna River.

An obvious prerequisite for the testing of these structures is that they will be attacked by the river during the 5 years the project will last. This is not a simple condition to fulfill as the attack of the river is very difficult to predict. A braided sand-bed river like the Jamuna (= Lower Brahmaputra) River in Bangladesh is characterized by frequent and substantial changes in planform during individual floods, causing the locations of attack by bank erosion to shift rapidly over the years (Coleman, 1969; Klaassen & Masselink, 1992). For the planning of bank protection works and for the maintenance of structures like river training works for bridges in general and for the test structures of FAP 21/22 in particular, a good insight is required into future planform changes. Hence prediction methods for planform changes of these rivers are urgently needed.

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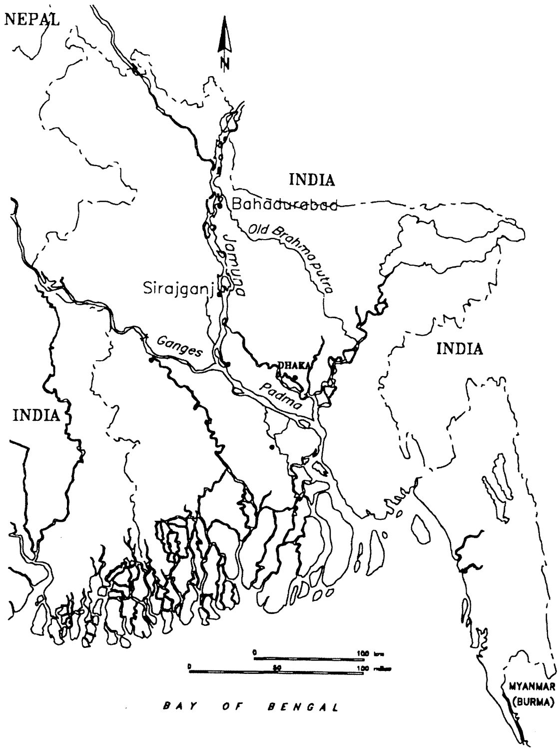


Figure 1. Map of Bangladesh with Jamuna River

The phenomena occurring in a braided river system are much more complex than the ones in meandering rivers. In a meandering river, bank erosion along outer bends and occasional cut-offs are the most prominent features, the channel width often remaining fairly constant along the river and in time. The same processes are active in a braided system, but in addition widening and narrowing are important and cut-offs occur frequently, all processes being very fast in the Jamuna River due to the fine nature of its bed material (almost uniform sand of 0.2 mm).

We report an ongoing project aiming at developing tools for the prediction of planform changes of the Jamuna River. Earlier results are reported by Klaassen & Masselink (1992). The basis for this study is an extensive set of satellite images, obtained during yearly low-flow seasons when there are no clouds and no floodplain inundations, so that the individual channels can be observed clearly. The change-detection images were constructed by combining two consecutive single-year images (see Figure 2). Red, purple and pink represent erosion and pale colours represent accretion. These images allow the identification of bank erosion rates, cut-offs and other morphological phenomena over one flood season. Some examples are shown in Figures 3 and 4. The satellite images are supplemented by soundings and other information on the river system. For more information on the satellite imagery and their use together with other data we refer to Klaassen & Masselink (1992).

The satellite images were used to identify underlying processes and to derive prediction methods for each of them. In a next step we combine these methods in an integrated way to make predictions for the changes in the planform at specific locations along the Jamuna River. The present paper concentrates on this last step and discusses the approach taken, together with its possibilities and limitations. The prediction methods aimed at will form tools for the assessment of morphological changes that occur autonomously as well as in response to, for instance, bank protection works.

For reference we give some characteristics of the Jamuna River. The water level slope decreases gradually from 0.1 to 0.06 m/km. The bed material is fairly uniform and its median grain size (D_{50}) varies from 0.25 mm near the Indian border to 0.16 mm near the confluence with the Ganges River. The annual flood is about 60,000 m^3/s, and during low flow conditions the discharges are between 4,000 and 12,000 m^3/s. The number of major braids varies between 2 and 3 per cross-section and the total width of the braid belt varies between 5 and 17 km. Flood conditions prevail from June to November, whereas the low-flow season lasts from December to April. For more details on the Jamuna River we refer to the bench-mark paper by Coleman (1969) and to more recent literature (Bristow, 1987; Klaassen & Vermeer, 1988a and 1988b; Klaassen & al, 1988; Klaassen & Masselink, 1992; Thorne, 1993).

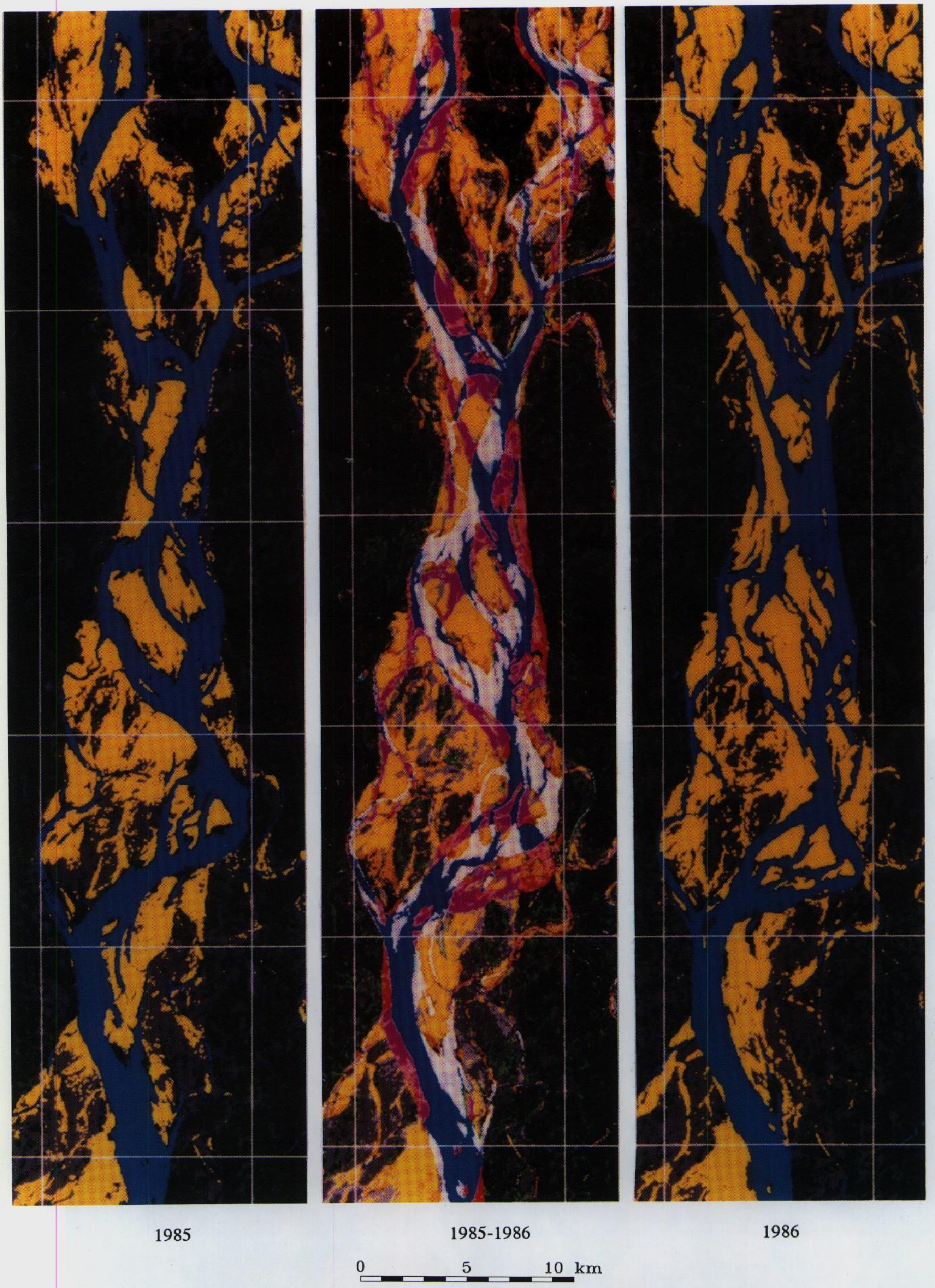


Figure 2. Single-year and change-detection images

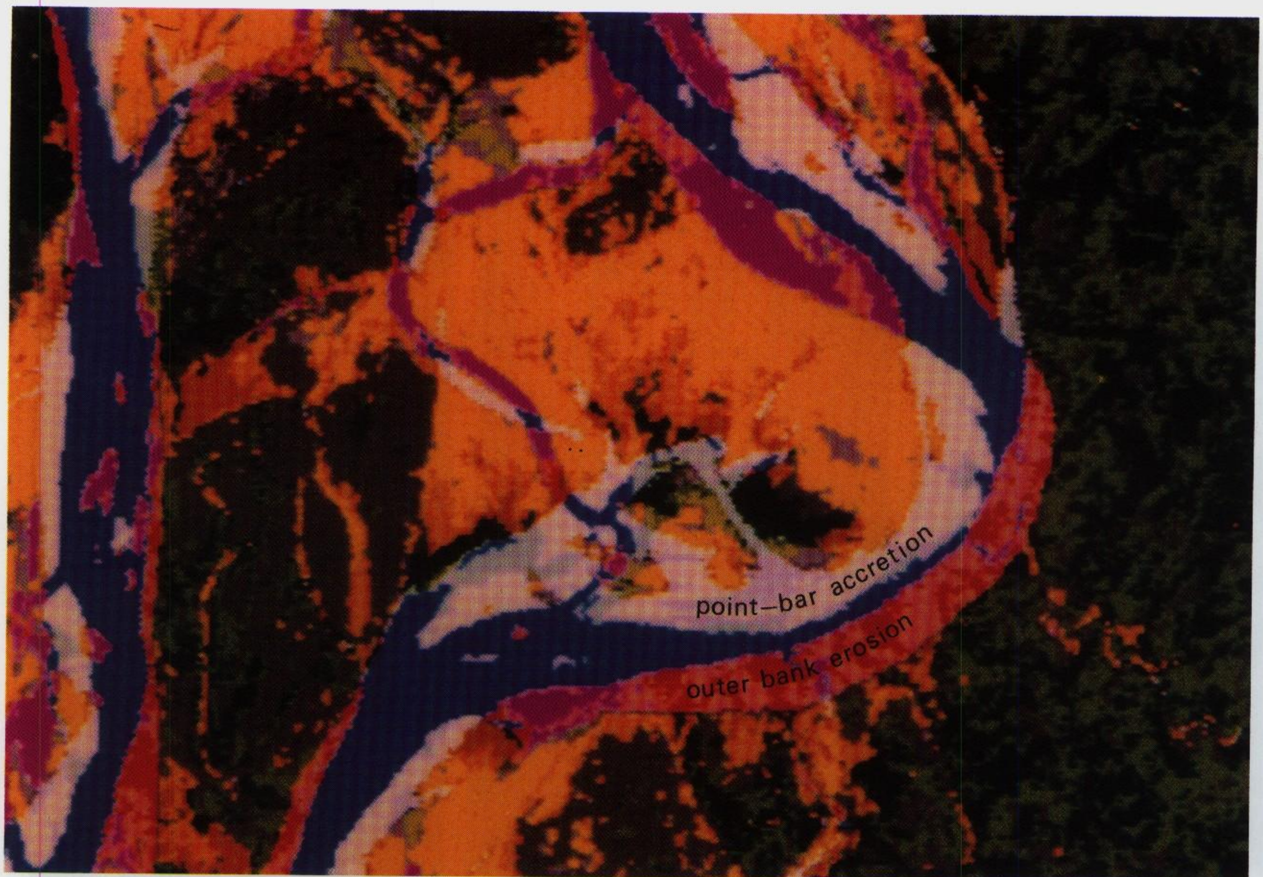


Figure 3. Change-detection image of bend erosion

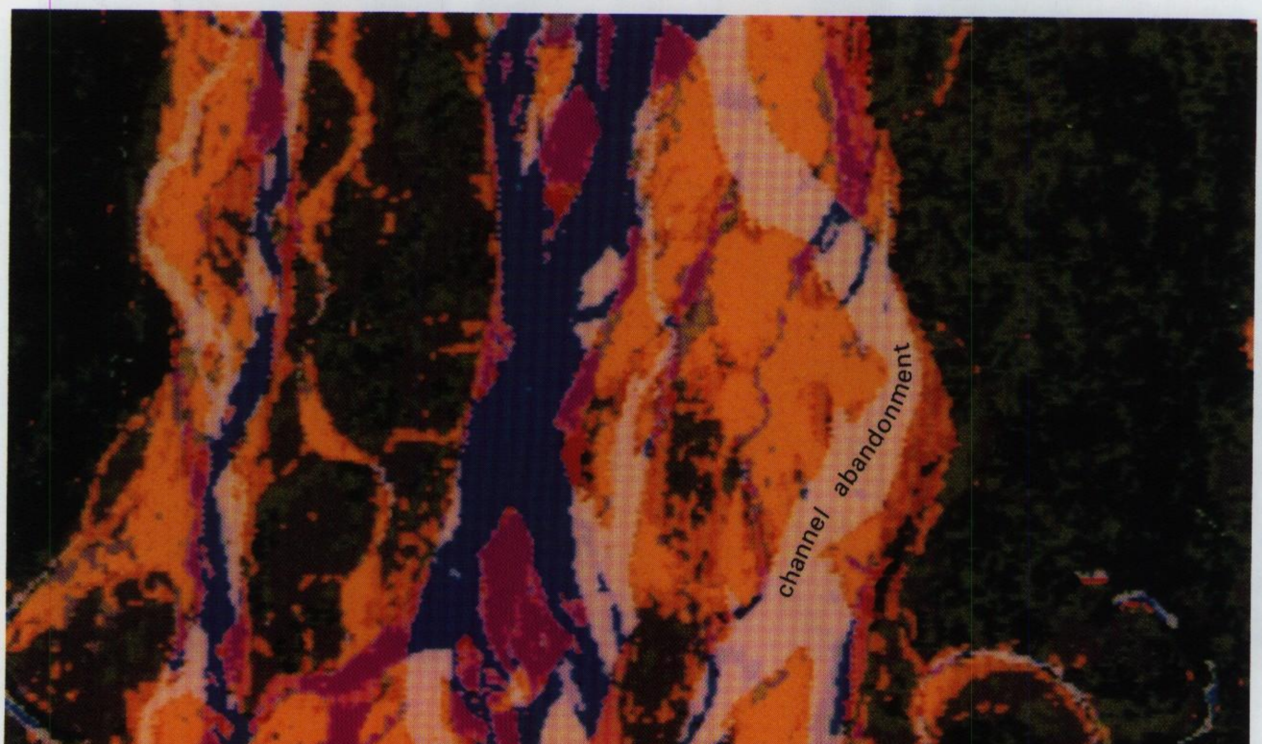


Figure 4. Change-detection image of channel abandonment

PROBLEMS OF PREDICTABILITY

The processes in the Jamuna River are so complex, that they sometimes seem almost random. Therefore, it is important to reflect upon the predictability of these processes. The predictions are based on initial conditions, boundary conditions and the formulation of the predictive model. We discuss first how all these factors put limits to the predictability and in the next section how considerations of predictability lead to a choice of the type of model to be used.

The initial conditions are determined from observations, which usually have limited accuracy and do not provide complete information. In particular, the following problems can be mentioned:

- the resolution (pixel size) of the satellite images is on the order of 50 m;
- there are no data on the morphological changes during a flood (only the net end result can be seen on the satellite images taken in the dry season);
- cross-sections are not available for every channel;
- even when a cross-section is available for a certain channel, it is not necessarily representative because of the strong non-uniformity of the channels;
- inundated banks cannot be distinguished from eroded banks on the satellite images (hence, higher stages produce spurious bank erosion on the images).

The boundary conditions include the upstream input of water and sediment, the downstream water levels and the properties of the surrounding terrain. Here, the problems are not only related to shortcomings in observations, such as the limited information on soil inhomogeneities. Problems also arise because the boundary conditions are affected by complex dynamical systems with their own limited predictability, in particular by meteorology and geology.

The meteorological processes determine the discharges. As long-term meteorological predictions are not possible, discharges must be treated as stochastic inputs. The planform changes are very sensitive to the discharges. Magnitude and duration of a flood determine the travel distances of wandering bars during one year, and hence whether or not such a bar arrives at a bifurcation. The arrival at a bifurcation may induce the rapid silting up of one of the bifurcated channels, which would have remained open otherwise. This represents one of the main thresholds in the system. Another influence of meteorology is that, on larger time scales, climate changes may affect the downstream boundary through sea level rise.

Bangladesh lies in one of the most active tectonic zones of the world (Coleman, 1969) and the influence of tectonics on the rivers of Bangladesh is unusually high (Baker, 1986). It is generally recognized that major avulsions are controlled by tectonic movements (e.g. Coleman, 1969), but there are indications that also the channel patterns within the present river course are influenced in this way. This might explain why channels in the river seem to have preferred courses. The influence of tectonics is currently also being studied on the basis of the satellite images.

Predictions covering a long period are also made difficult by the possible occurrence of exceptional events. A major earthquake could completely alter the present-day trends and result in a completely new orientation of the river courses (cf Coleman, 1969).

Theoretically, a feasible predictive model can be derived from fundamental laws for the motion of water and sediment by a formal integration over time and space. This is not a direct integration from a small to a large scale, but a series of integration steps to ever higher levels in a cascade of scales. Due to the non-linearity of the system, each step requires the introduction of empirical closure relationships. This implies that even 'theoretical' models become to a large extent empirical, and hence inaccurate.

Another problem is that the model may be very sensitive to initial conditions, thus producing chaotic behaviour. Phillips (1992a and 1992b) discusses general arguments of why chaotic behaviour is likely to be very common in geomorphic systems. In river morphology this is still a hardly explored subject, but the sensitivity of channel abandonment to discharge as well as the non-periodicity of the meanders in the numerical simulations by Howard & Knutson (1984) and Crosato (1990) do suggest chaos. Furbish (1991) explains explicitly that bend shape variations can be ascribed to the sensitive dependence of meander planforms on initial conditions and entrance conditions.

DETERMINISTIC, STOCHASTIC AND STATISTICAL MODELS

Considerations on predictability for the period of interest prescribe the type of model to be used. Table 1 gives an overview. We illustrate this by discussing models for planform changes of meandering rivers first. The boundary conditions are the discharges and the properties of the surrounding terrain. The discharge hydrograph can be more or less predictable, for instance in rivers with regular monsoon flood waves, or to a large extent irregular and unpredictable.

Planform changes are very difficult to predict if the period is short. Banks erode by mass failure during discrete events when a critical stability criterion is exceeded. This does not happen uniformly along the whole bank, but each time in small zones only, seemingly at random. This means that the surrounding terrain properties are stochastic boundary conditions and that the only modelling approach possible is a stochastic one.

For intermediate periods and relatively regular discharge hydrographs, a good prediction of river meandering is possible. The modelling can be described as deterministic. However, the sensitivity of the model to initial and boundary conditions and the possible occurrence of cut-offs make that the model should contain stochastic elements as well.

For longer periods, the question whether a certain place at a certain time is attacked is determined by the statistical distribution of water and land over a long period. Hence a statistical model can be applied, in which the spatial distribution of frequencies of water occurrence reflects patterns of soil properties, geology, terrain elevation and local human interference. This approach was used for determining the design conditions for a bridge over the Jamuna River (with an economic life time of 50 years and the river completely changing its planform in 5 to 10 years). The statistical distribution for the period 1973-1992 is shown in Figure 5-a, where colour intensities indicate the number of years in which locations were a part of the deep channels. Figure 5-b represents a superposition of the successive channel planforms from the same period.

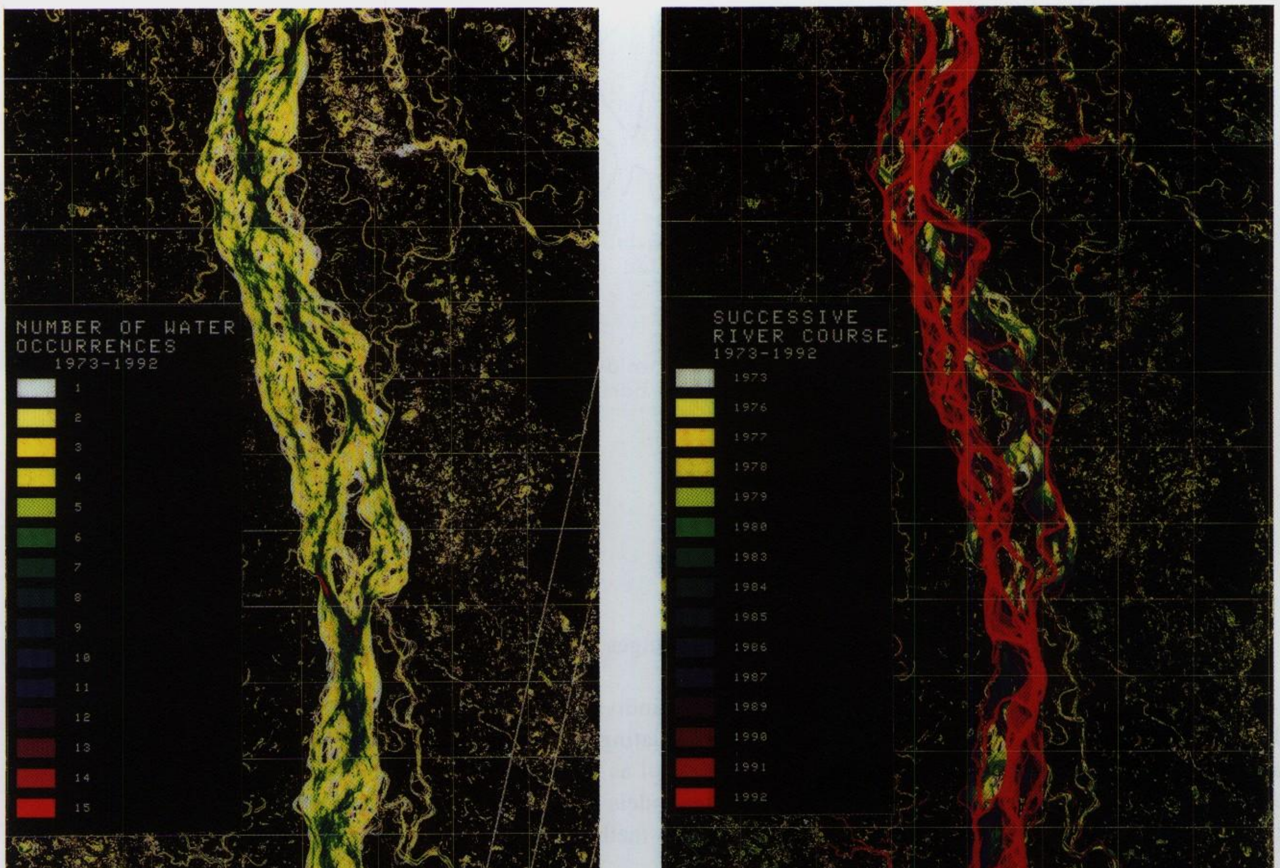
Similar considerations hold for the choice of a model for a braided river like the Jamuna River. For intermediate simulation periods (one to three years), however, the greater complexity and the greater importance of thresholds cause the stochastic elements to be more important here than for meandering rivers.

boundary conditions	model sensitivity to boundary conditions	duration of simulation period relative to characteristic time scale of morphological processes		
		short	intermediate	long
predictable	low	deterministic	deterministic	deterministic
	high	deterministic	deterministic / stochastic	statistical
unpredictable	low	stochastic	deterministic for time averages	statistical
	high	stochastic	deterministic / stochastic	statistical

Table 1. Selection of type of model to be used

MODELLING CONCEPT

As the derivation of a feasible predictive model for the Jamuna River from fundamental laws would involve so many integration steps that many empirical closure relationships would have to be introduced, we believe that it is better to induce a model directly from the observations. This leads to an approach in which we (1) decompose the overall phenomena into a number of individual processes at a high level of aggragation, (2) investigate the individual processes separately, and (3) integrate the individual processes into a combined predictive tool. The high level of aggragation means that process descriptions represent the complex behaviour of large-scale river elements rather than the elementary behaviour of infinitesimal volumes of water and sediment. The individual processes at a



(a)

Statistical distribution
of water occurrences

(b)

Successive river courses

Figure 5. Multi-temporal planforms from period 1973-1992

high level of aggragation are channel migration, mid-channel bar formation, behaviour of bifurcated channels (i.e. width adjustment, channel abandonment and channel creation) and the migration of confluences and bifurcations. Some examples are shown in Figure 6.

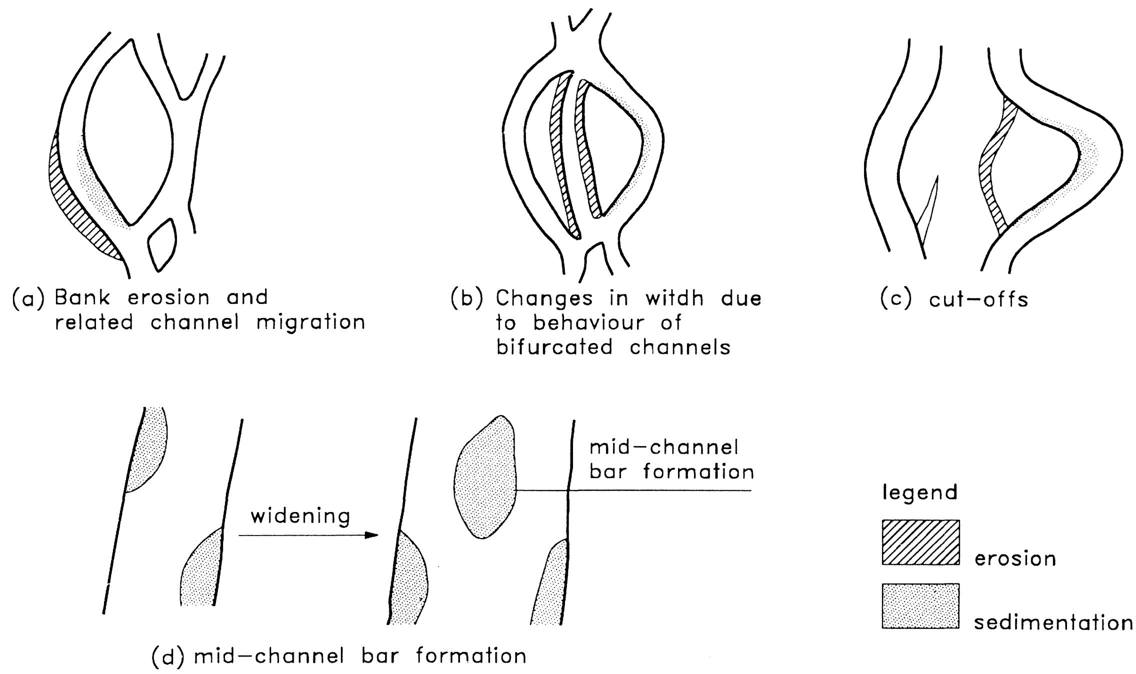


Figure 6. Planform changes in a braided river

We consider two ways of combining submodels for individual processes into a prediction tool, see Figure 7. The first way is already operational and consists of evaluating the combined action of the individual processes by hand according to a formal procedure. We refer to this tool as the 'methodology' and show its application in a later section. The second way consists of combining the submodels in a computer model. The development of the latter just started. We use the general word 'model' for both the methodology and the computer model.

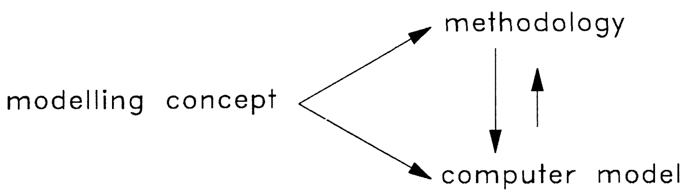


Figure 7. Modelling concept and prediction tools

The methodology and the computer model have stochastic and deterministic elements. The general structure of the computer model will be a Monte Carlo simulation for both stochastic processes (e.g. channel abandonment) and stochastic input data (e.g. discharge hydrograph). The Monte Carlo simulation will not produce a continuous spectrum of possible outcomes, because the system contains certain thresholds between whether events occur or not, for instance the silting up of a channel due to the arrival of a wandering bar at a bifurcation. Hence the Monte Carlo simulation can be represented as a tree of events, similar to fault trees in risk analyses. This is the essence of the procedure in the methodology.

In principle, two types of methods are possible for the description of the processes involved, one related to a bar approach and one related to a channel approach, see Figure 8. In the bar approach, the pattern changes are taken to be determined primarily by changes of a submerged bed topography. In the channel approach, the patterns are schematized as a network of migrating bends, interconnected at bifurcations and confluences that are also migrating. Within this network, new channels can be created and existing channels can be abandoned. We mainly follow a channel approach, but with some elements from the bar approach.

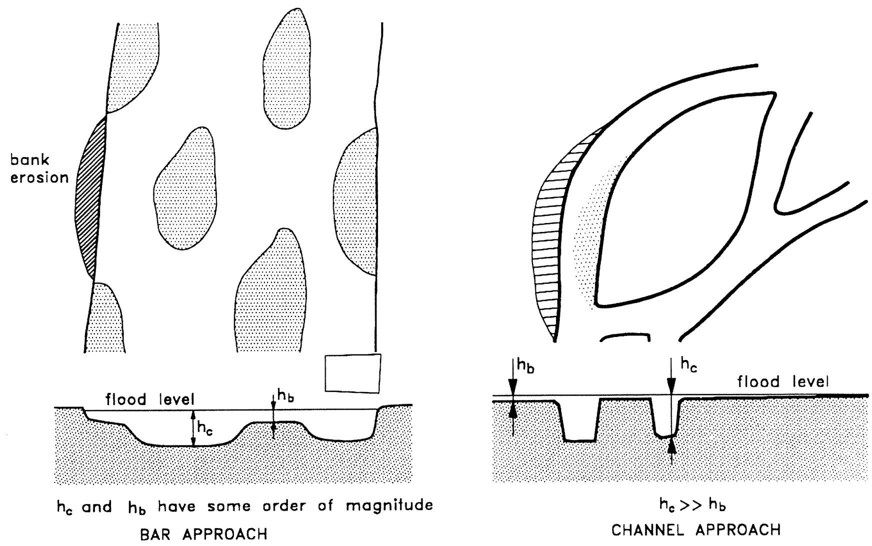


Figure 8. Bar approach and channel approach

MODEL COMPONENTS

The model components are submodels for the individual processes. Generally, they describe planform changes as a function of geometry and discharge. In addition, the preprocessing and postprocessing of data form an important part of the computer model.

Channel Migration:

Several mathematical models for river meandering exist. Roughly, they can be subdivided into five categories. Listing them in the order of increasing complexity, these categories are:

(1) Simple formulas in which bank migration rates are a function of local channel curvature (Hickin & Nanson, 1984);
(2) Simple kinematic models in which bank migration rates are a function of local and upstream channel curvatures (Ferguson, 1983; Howard, 1983; Howard & Knutson, 1984);
(3) Meander models based on the equations for water flow and bank migration in curved equiwidth channels (Ikeda et al, 1981);
(4) Meander models based on the equations for water flow, sediment transport and bank migration in curved equiwidth channels (Johannesson & Parker, 1989; Crosato, 1990);
(5) Meander models based on the equations for water flow, sediment transport and bank migration in channels with arbitrary geometries (Mosselman, 1992).

Klaassen and Masselink (1992) followed the approach of Category 1 by studying the correlation between bank erosion and local radius of channel curvature. However, a model based on this type of formulas cannot simulate bend migration properly, as was pointed out by Howard & Knutson (1984). We therefore now use the approach of Category 2 by using a linear relation between bank erosion and a weighted average of local and upstream channel curvatures. For that, we re-analyzed the bends in the Jamuna River and revised the relations between bank erosion and curvature. The sophisticated models from Categories 4 and 5 would require too much computation time and are not justified in view of the data available. As Parker (1983) argues that models from Category 2 are equivalent to the model of Ikeda & al (1981) in Category 3, we think that Category 2 indeed serves our purposes the best.

Mid-channel Bar Formation:

The formation of mid-channel bars is modelled as a function of the width-to-depth ratio of the channel. This is the main bar-approach element in the model. Mid-channel bars are formed in wide and shallow channels and, in their turn, enhance channel widening by further outward deflection of the channels on either side. Struiksma & Klaassen (1988) base a criterion for mid-channel bar formation on the stability of linearized equations for water and sediment motion. A linear prediction of exponential growth, however, does not necessarily imply that the bar will actually reach the water level, because non-linear interactions may prevent growth beyond a finite amplitude. The criterion therefore needs recalibration.

Behaviour of Bifurcated Channels:

Changes in the relative importance of bifurcated channels are determined basically by the distributions of discharge and sediment transport at the bifurcation. The sediment transport distribution is very difficult to assess, but will strongly depend on the geometry of the bifurcation. Therefore, the changes in the bifurcated channels will be related directly to bifurcation geometry. Channel abandonment and channel creation arise as special cases of the behaviour of bifurcated channels. A new channel appears when a mid-channel bar emerges from the water level or when an avulsion or a cut-off occurs. The latter case can only be simulated with the computer model if the position of a probable new channel has been specified by the user in advance. New channels frequently occur in connection with a drainage channel which was probably formed during the fall of the previous flood, but this is not always the case.

Channel cut-offs are a special type of channel creation, often occurring in combination with simultaneous channel abandonment. Different from what was suggested implicitly by Klaassen & van Zanten (1989) and Klaassen and Masselink (1992), it appears that in the Jamuna River the cut-off ratio (i.e. the ratio between the lengths of the old and the new channel) is less important than the angle between the channel to be abandoned and the channel upstream. Figure 9 shows that the probability of channel abandonment is negligible if this deflection angle is less than 30°, but increases for higher values of the deflection angle. Bifurcation asymmetry is also an important parameter.

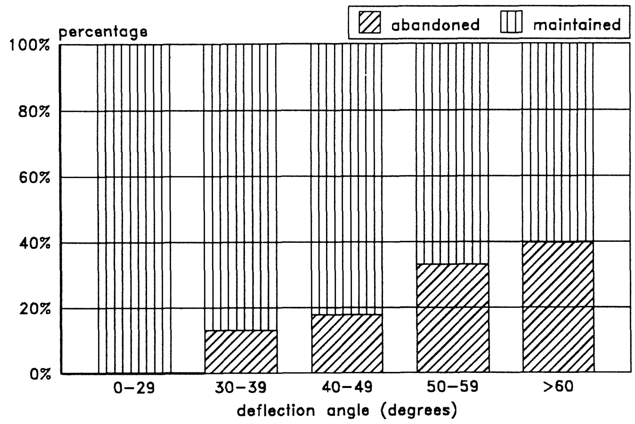


Figure 9. Probability of channel abandonment
as a function of deflection angle

Migration of Confluences and Bifurcations:

For the time being, no separate formulation for the migration of confluences and bifurcations is included. The migration is assumed to result simply from nearby channel migration and the formation and coalescence of mid-channel bars.

Pre- and Postprocessing:

An important element in the envisaged computer model is the preprocessing and postprocessing of data. The preprocessor must allow that the channel network is derived directly from the digital satellite image. For this, we will use the skeleton algorithm of Hilditch (1969), also used for rivers by Moll and Overmars (1990). The postprocessor must produce a map in which colour intensities indicate the probability that a pixel becomes water. As a matter of course, this will also provide the probabilities of bank erosion, bend cut-off, etc.

SAMPLE APPLICATION OF METHODOLOGY

To demonstrate the potentials and the limitations of the modelling approach, some results of its application to a reach of the Jamuna River are shown here. The reach is located upstream of the confluence with the Ganges River. It is slightly untypical for the Jamuna River in that the number of braids per cross-section, and hence the braiding intensity, is less compared with the more upstream reaches. This is the very reason why we selected this reach here, because it serves as a clearer example than some of the other reaches where the methodology was applied. Some results of the application of the methodology are shown in Figure 10.

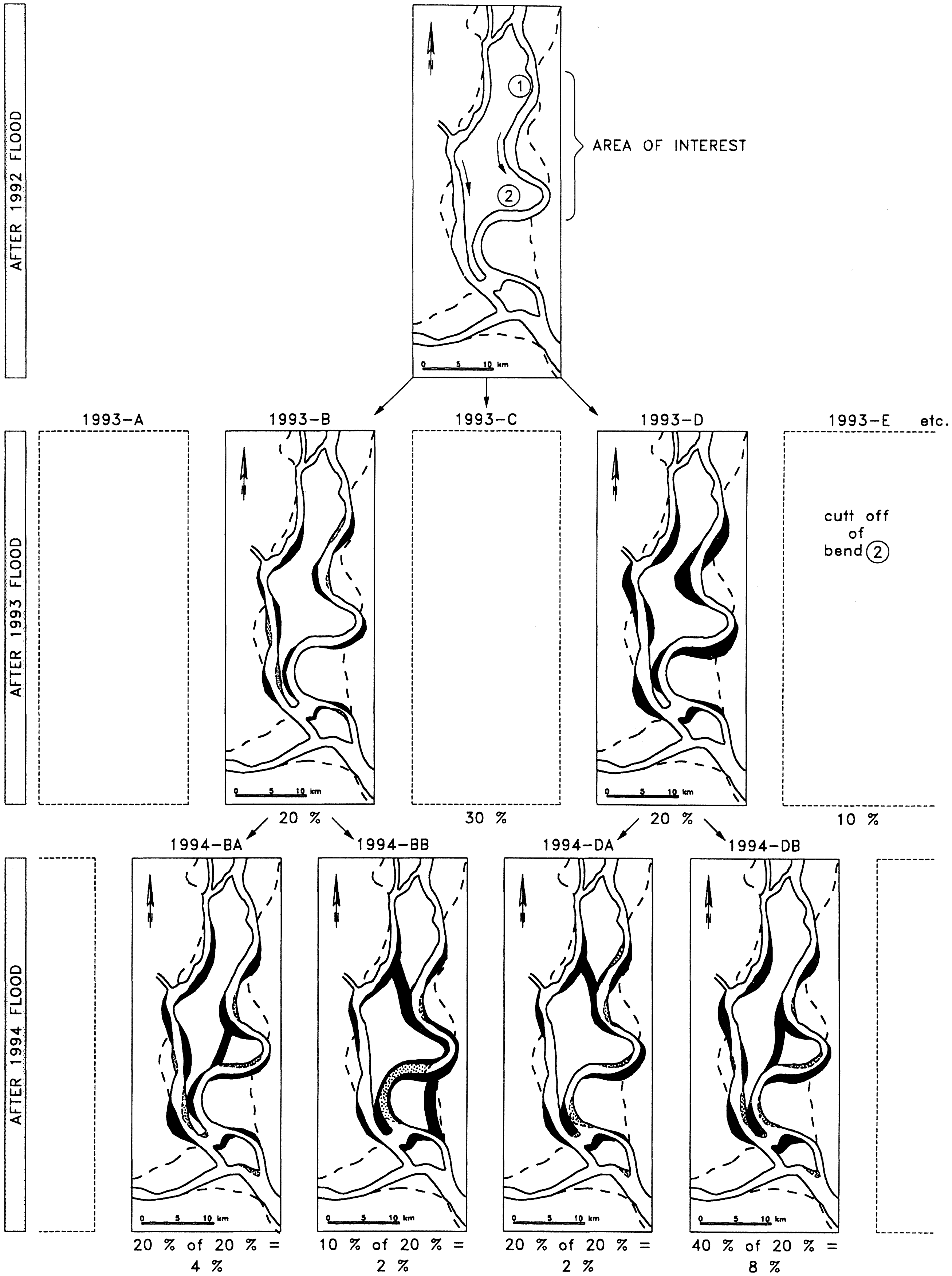


Figure 10. Sample application of methodology

The area of interest is located along the left bank of the river. Two bends are present, marked as 1 and 2. The question to be answered is: what is the probability that the bank in bend 2 will still erode in the 1995 flood season and afterwards ? Figure 10 shows that several developments can take place. During the 1993 flood season, the bank erosion along the various bends may be minor or major, depending on the magnitude and the duration of the flood. Note that the two developments shown correspond to only 40% of the possible developments. The probability that a cut-off of bend 1 occurs is certainly not negligible. Each of the possible planforms in 1993 will develop further in 1994. A cut-off conform the development 1994-DB becomes more and more probable. This will lead to a reduction of the bank erosion along bend 2. Note that also development 1994-BB leads to such a reduction. The overall probability that the bank erosion along bend 2 will stop after 1994 is at least 2 + 8 = 10%, but many other developments (not shown in the figure) may also result in such a reduction. We estimate that the probability of no further erosion in 1995 is about 50%. Note also that for all developments foreseen in Figure 10, the erosion along bend 1 will continue. From the two potential sites for test structures a location along bend 1 is to be preferred.

The number of possible developments obviously increases with the number of years considered, which makes the analysis complicated and time-consuming. This demonstrates the need for a computer model.

CONCLUDING REMARKS

In this paper we have outlined a modelling concept for the prediction of planform changes in braided sand-bed rivers. Because of the stochastic approach necessarily taken here, the possible developments can only be expressed in terms of probability. Initially the future developments can be predicted with a fairly high accuracy, but when the ratio of simulation period to typical time scale of the morphological changes becomes larger, the number of possible developments increases and the accuracy of the prediction of the actual development decreases.

The components of the model were mainly derived from the analysis of a 20 year long series of satellite images of the Jamuna River during low flow conditions. Essentially these satellite images allow only a two-dimensional picture, whereas the actual developments are definitely affected by three-dimensional phenomena (like spiral flow, bar heights, etc.). A further refinement would be possible if the three-dimensional bed topography could be used. In future, radar images from satellites can help in providing such a three-dimensional picture by also yielding the extent of the flooding during the flood season when clouds prevent observation with optical and infrared sensors.

One particular aspect of the Jamuna River is that, due to the fine nature of the bed and bank sediments, morphological changes are also substantial during lower stages. More insight in the response of the river to these lower stages is needed to improve the prediction techniques for the various model components.

Furthermore, it should be stressed that until now the methodology could only be tested over the most recent (1992) flood. As the prediction covers a number of years, it is required to obtain experience by comparing predicted and actually observed planform changes in the coming years too. This also raises the point of 'verifying' or 'falsifying' the modelling concept. This can only be done in a statistical sense. Methods for verification are currently being developed.

In long-term perspective, we consider the present development of prediction tools as a first step towards an early warning system for undesired planform changes during a flood. Such a system would be based on numerical predictive models, discharge measurements, soundings and radar remote sensing, linked together through data assimilation. Radar penetrates clouds and can sense bed topography patterns up to tens of meters deep (cf Vogelzang & al, 1992).

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MORPHOLOGICAL CHANGES IN A LARGE BRAIDED SAND-BED RIVER

by

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ABSTRACT

Processes governing morphological changes in the braided Lower Brahmaputra river have been studied. We present results on width adjustment, channel abandonment, bend migration, the influence of tectonics and correlations with the magnitude of the annual flood.

INTRODUCTION

The Brahmaputra is a large braided sand-bed river that flows through India and Bangladesh. The total width of its braid belt varies between 5 and 17 km and individual channels are up to 2 km wide. The annual flood is about 60,000 m^3/s. Scour depths can reach 40 m and bank erosion rates can locally be as high as 1000 m/year. The associated rapid planform changes are very complex and include phenomena like bend migration, formation and propagation of bars, channel creation, channel abandonment and migration of confluences and bifurcations. Previous studies of these processes are reported by Coleman (1969), Bristow (1987), Klaassen & Vermeer (1988a and 1988b) and Klaassen & Masselink (1992). General considerations on predictability and model concepts are discussed by Klaassen & al (1993). Here we present the main results from our studies in 1992. For these studies we used daily discharges from Bahadurabad station, cross-sectional data and an extensive set of satellite images from Landsat MSS, Landsat TM and MOS-MESSR sensors of the Lower Brahmaputra in Bangladesh. The images cover almost every year from 1973 to 1992. Noorbergen (1993) describes the processing of these images, which includes the production of multitemporal change-detection images.

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RELATION BETWEEN BANK EROSION AND DISCHARGE

The discharge through a particular channel within the braid belt can be estimated from the total discharge by assuming that the discharges are distributed over the channels in proportion to the conveyance of each channel. Cross-sectional data, however, were not available for every channel, and even when a cross-section was available, it was not necessarily representative because of the strong non-uniformity of the channels. Indeed, attempts to correlate morphological changes with discharges thus obtained yielded poor results. We then tried to find a correlation between an overall measure of planform change and a parameter characterizing magnitude and duration of the total annual flood. Figure 1 shows the relation between the total area of eroded land along 14 major bends and the fourth moment of the discharge record, α_4, defined as

$$\alpha_4 = \frac{1}{T}\int_0^T \{Q(t)\}^4 dt$$

in which *Q(t)* denotes discharge as a function of time and *T* represents one year. Discharges were truncated at the bankfull value of 44,000 m^3/s. Here a weak trend that the amount of bank erosion increases as discharge increases becomes visible. The trend is less clear for lower moments of the discharge record with an exponent of, for instance, 1 or 2.

Inundated banks cannot be distinguished from eroded banks on the satellite images, so that higher stages produce spurious bank erosion on the images. The arrows in Figure 1 indicate in which direction the points would move if a correction for this spurious erosion could be made. It must be noted, however, that spurious bank erosion is less significant than spurious bank accretion because the eroding banks are usually steep.

WIDTH ADJUSTMENT

The hydraulic geometry of individual channels changes continuously due to changes in the supply of water and sediment from upstream. This supply depends on the distribution of water and sediment at upstream bifurcations. The distribution of discharges over the bifurcated channels can be calculated easily when the geometry of the channels is known, but the distribution of sediment transport is very difficult to assess. As this distribution depends on the geometry of the bifurcation, we tried to find a correlation between width adjustment and upstream bifurcation geometry. The latter was represented by the deflection angle, i.e. the angle between a bifurcated channel and the channel upstream, and by parameters expressing the degree of bifurcation asymmetry. We could not find a clear correlation. As an example, we show the relation between width adjustment and deflection angle in Figure 2. Width adjustment appears here more or less like a random process.

CHANNEL ABANDONMENT

Channels are frequently abandoned as a result of chute cut-offs and channel avulsions. We tried to correlate channel abandonment with the key parameters of the model for bend cut-offs by Klaassen & van Zanten (1989) as well as with the bifurcation geometry parameters used in the study on width adjustment. Correlations with the latter group of parameters gave the best results. The relation between the frequency of channel abandonment and the deflection angle is shown in Figure 3. Comparing the clear trend in this figure with the randomness in Figure 2, we conclude that channels are abandoned through shallowing rather than narrowing.

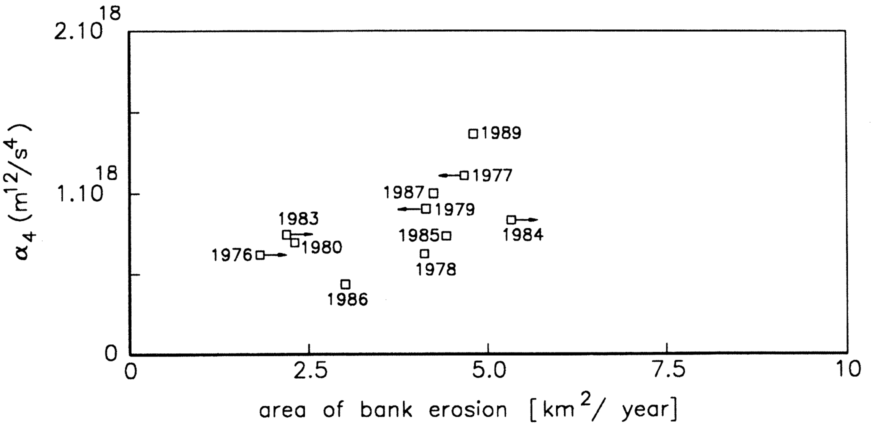

Figure 1: **Relation between erosion area and fourth moment of flood hydrograph.**

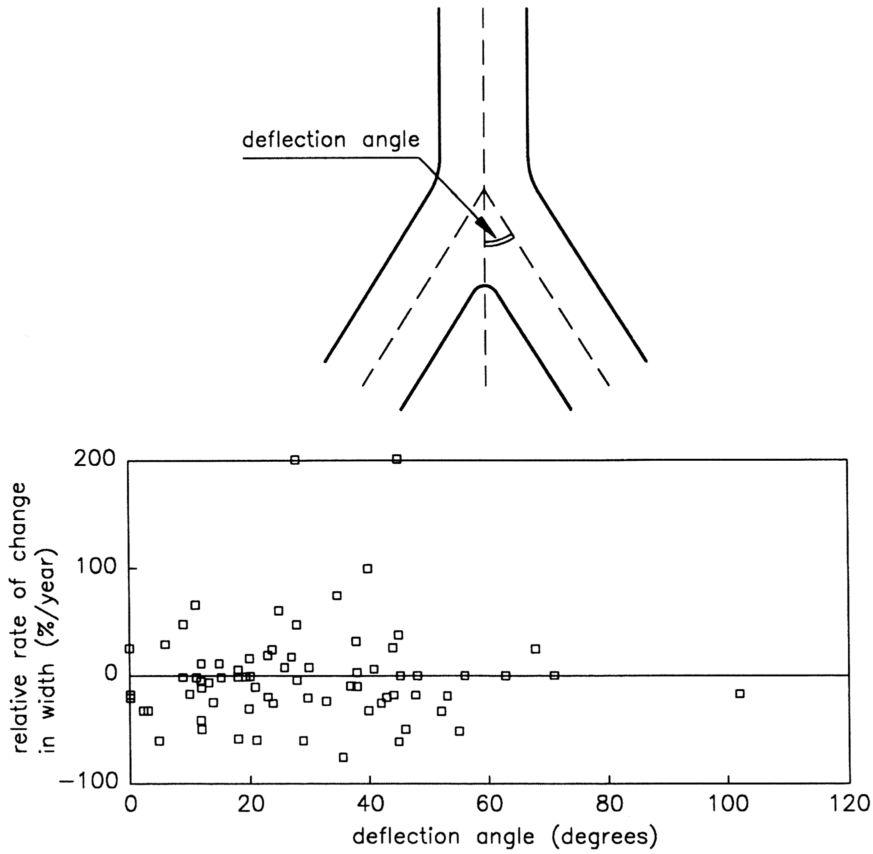

Figure 2: **Relation between width adjustment and deflection angle.**

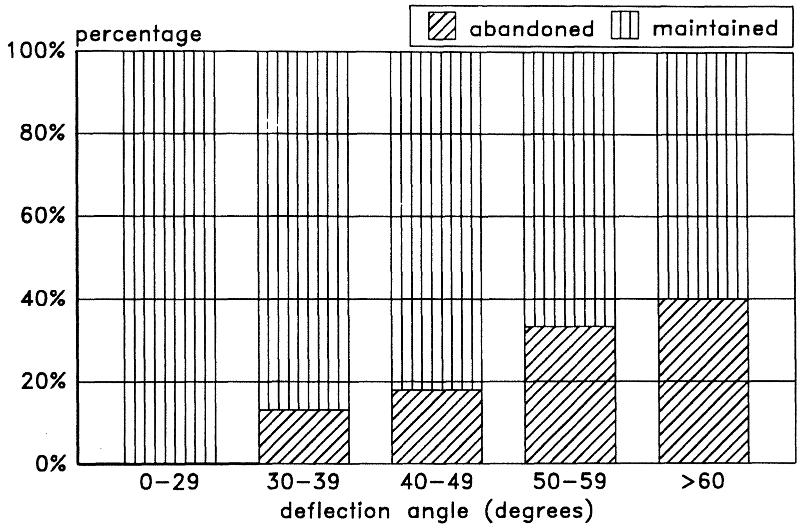

Figure 3: Relation between probability of channel abandonment and deflection angle.

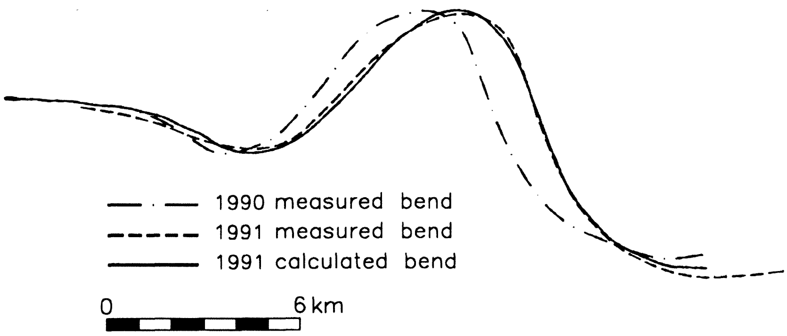

Figure 4: Comparison between observed and simulated channel migration for a large bend around latitude 24° 0′.

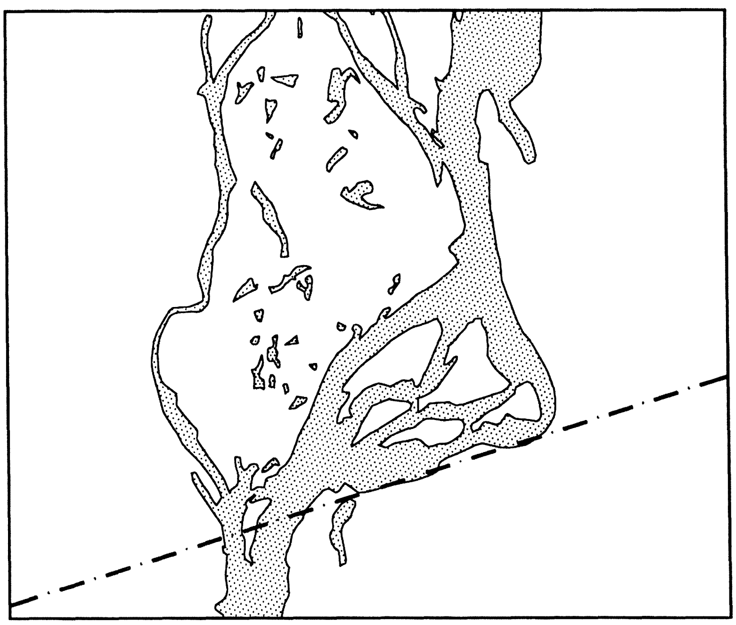

Figure 5: Inhibition of channel migration at a fault by tectonic block activity.

BEND MIGRATION

Klaassen & Masselink (1992) studied bend migration by correlating bank erosion rates with local channel curvatures. We attempted to improve this by simulating the migration of a few bends with a simple kinematic meander model, in which bend migration is a function of local and upstream channel curvatures (cf Howard & Knutson, 1984) and also a function of the absolute value of the sine of the angle between channel centre-line and direction of maximum valley slope. The latter dependence was assumed to represent the downvalley migration due to cross-channel flow at high stages in analogy to the downstream propagation of a dredged trench. Figure 4 shows the results for the migration of a large bend around latitude 24° 0′, close to the confluence with the Ganges river. The characteristic length scale in the convolutional relation between migration and upstream channel curvatures was 10 km. Computed planform changes appeared to be more sensitive to errors in the position of straight reaches than to errors in curved reaches.

INFLUENCE OF TECTONICS

The Lower Brahmaputra river lies in one of the most active tectonic zones of the world. The tectonic activity is related to the collision between the Indian and Eurasian plates (Molnar & Tapponier, 1977), the subsidence in this zone being the direct counterpart of uplift in the Himalayan belt. The activity has fractured the terrain into various geological compartments or blocks, separated by vertical fault planes. We identified these faults by an analysis of lineaments on the satellite images. The major faults are presented in Figure 6. Details are reported by Hartmann & al (1993).

There are indications that the channel pattern within the Lower Brahmaputra is influenced by differential uplift or subsidence and tilting of the geological compartments. Firstly, the channels are sometimes remarkably straight in directions parallel to the faults. Secondly, changes in planform are sometimes difficult to explain from an autonomous motion of water and sediment. An example is shown in Figure 5, where the downstream translation of a bend at latitude 24°10′ seems to be inhibited between 1986 and 1987 by an apparent rectilinear obstacle complying with one of the faults we identified in both the braid belt and the surrounding terrain. Field evidence of vertical terrain motions is needed to confirm these findings.

CONCLUDING REMARKS

We studied the planform changes in the braided Lower Brahmaputra river by using satellite images, discharge records and cross-sectional data. Some conclusions can be drawn, but the phenomena are so convoluted that it is difficult to extract information on individual underlying mechanisms from observations only. It is necessary to bring descriptions of the underlying mechanisms together in a model to see whether their combined behaviour can reproduce the observed morphological changes. We started the development of a probabilistic predictive model. Its general concepts are described by Klaassen & al (1993).

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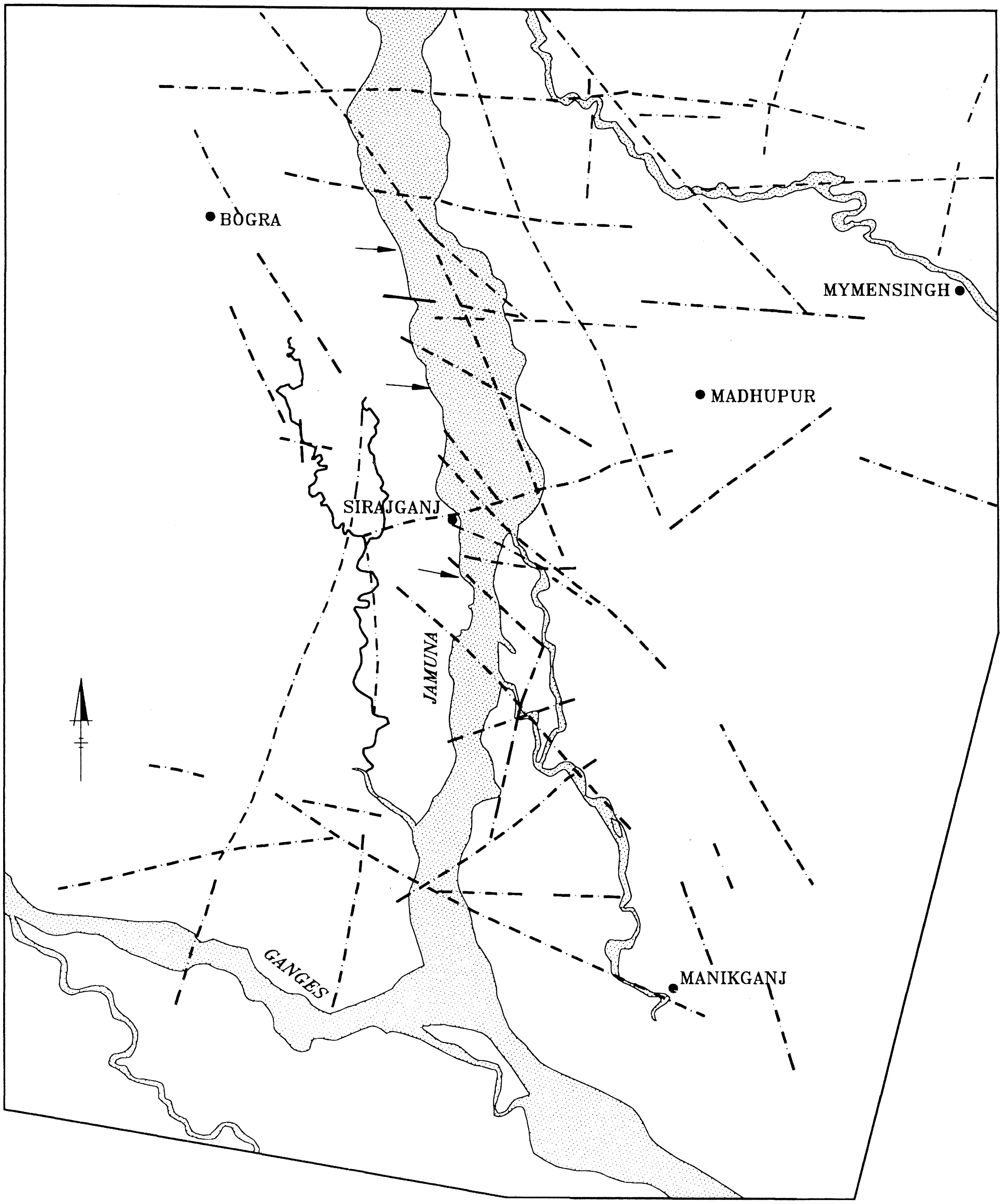

Figure 6: Major faults in the Bengal Basin as inferred from an analysis of lineaments.

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